DEPARTMENT OF DEFENSE

MILITARILY CRITICAL TECHNOLOGIES

PART III: DEVELOPING CRITICAL TECHNOLOGIES

SECTION 7: ENERGY SYSTEMS TECHNOLOGY

November 1999

Defense Threat Reduction Agency
Dulles, VA

SECTION 7—ENERGY SYSTEMS

Scope

Highlights

- Energy system technologies provide for power generation and energy conversion, energy storage, and power conditioning.
- The Joint Chiefs have recognized high-energy density power converters as a technology priority.
- The military's goal is to increase system power densities by two to five times, depending upon the specific system.
- Power converters typically take up approximately 50 percent of system volume.
- Stringent military requirements demand reliable, intelligent/survivable, and affordable energy systems that can perform in battlefield threat environments.
- Budget pressures and the military's need for reduced volume and weight, increased performance, and graceful degradation make it difficult for military and commercial compatibility.
- Advances in power electronics, packaging, and thermal management will drive the performance advances in the state-of-the-art.

OVERVIEW

This section discusses the developing critical technologies for energy systems embedded in the following subsections:

- Energy Conversion and Power Generation
- Energy Storage
- Power Conditioning
- Biological Energy.

Energy and power system technologies are among the least visible, and their functions are usually taken for granted because we assume that reliable power will always be available. However, many weapon system platforms, because of different energy and power requirements, integrate a host of diverse technologies for power generation, energy storage, and power conditioning. Because of the weapon system platforms' variance in application and mission criteria, a wide range of energy requirements exist. These platforms need not only pulsed or continuous power but also need many niches and diverse technologies to satisfy low-, medium-, and high-power requirements.

Factors that influence the development of military energy systems include the critical need to occupy smaller volume, have low weight, provide long life-cycle performance, and be highly reliable and survivable in threat and extreme environments. Because of the military's stringent performance requirements, the advances in power electronics packaging and integration and in thermal management will be the key drivers in the successful realization of the military's future vision. The Joint Chiefs have recognized high-density power converter systems as a technology priority, and these systems will require new technology design and packaging approaches that are expected to revolutionize the power electronics industry.

Specific load requirements (e.g., power level, duration, pulsed, or continuous) drive the system design and the component technologies. To a large extent, the power level required determines the primary energy source and often severely limits the options available to choose from. The mission duration is also a critical factor since certain power-system technologies have inherently useful lifetimes, while others are capable of continuous and extended missions. Finally, the distinctions between single-shot, repetitive, and continuous power systems are critical since the duty cycle places different stresses and performance requirements (e.g., voltage, current, frequency, and temperature) upon the components used. . . . Power levels range over many orders of magnitude—from milliwatts of continuous power in handheld electronic devices to terawatts in certain directed energy weapons. Durations range from small fractions of a second for single-shot, pulsed-power applications to months or even years for remote power and/or space systems (ATAR, p. I-3).

Figure 7.0-1 addresses the complex taxonomy of energy systems. As a real-world example, take a mobile platform (e.g., an air vehicle) as the system. Integrated mission requirements include the ability to hunt and kill (mobility, navigation, and lethality), to communicate, and to ensure the safety of the aircraft and its crew (environment and survivability). Each mission requirement results in the need for distinct subsystems driven by either continuous or pulsed power. The power supply system is, therefore, a conglomeration of energy conversion and power-generation systems driving energy storage, power conditioning, and pulse-forming networks. The energy systems are subject to strict constraints of thermal management, scalability, and integrated functionality. Beneath this layer lie the supporting technologies and components that make everything possible. Stepping from one function to the next reduces output and capability by less than perfect efficiencies.

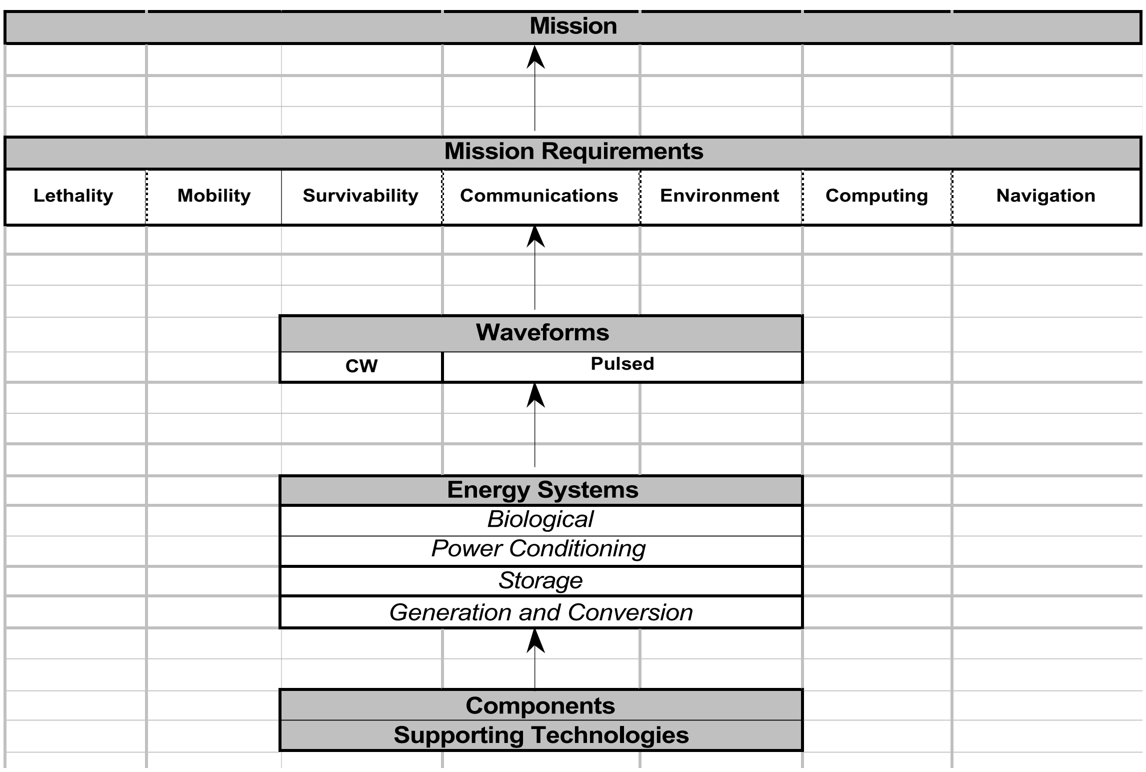


Figure 7.0-1. Energy Systems Taxonomy

RATIONALE

Energy is generally collected or available from a prime source at low-power levels and power densities. To meet common military load requirements, such as high power (density), the energy is released from storage over an extremely short duration and converted into pulsed-power form. Power is energy per unit time. Therefore, by compressing the duration of time over which energy is supplied, one achieves higher powers. After additional compression of the pulsed power, it is delivered to a load with great amplification of power and power density (see Figure 7.0-2).

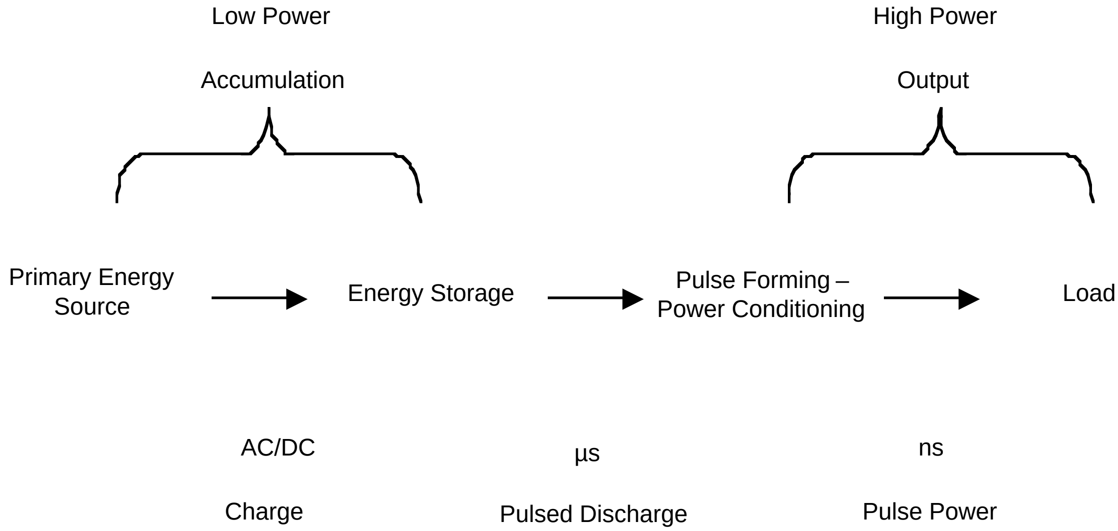


Figure 7.0-2. Typical High Pulsed-power System (Adapted From Pai, 1995)

In many cases, military energy requirements have a much broader range of demands than the commercial segment. Figure 7.0-3 shows the large variation in peak power output and duty cycle for several types of missions. With the exception of a few commercial radars, navigation systems, communication systems, and industrial processes, typical commercial energy systems do not have the high-output requirements of the military systems shown in Figure 7.0-4. Because of this disparity, only a portion of advanced technologies developed to serve as commercial energy system components can be directly transferred into military systems. Commercial-off-the-shelf (COTS) technologies are competitive in size and cost and are enabling when components can meet requirements of military systems.

There is an enduring military vision for reducing weight and volume while increasing performance, reliability, and, most importantly, survivability. This is true for most sizes of applications—from the individual soldier to the largest platforms. Figure 7.0-5 highlights current Soldier Power System and Land Warrior power requirements, and Figure 7.0-6 highlights the electrical power applications for a sample mobile platform (repetition rates are measured in pulses per second). In the latter case, system design is a significant challenge because of the need for both continuous wave (CW) and pulsed subsystems and dense packaging. In one sense, Soldier Power Systems are a mobile platform; however, we mention them specifically because of their unique requirements.

> Equipment for the dismounted soldier must be both compact and rugged. Availability of fuel, specific energy, specific power, minimal signature (electronic, thermal and acoustic), simplicity of operation, and environmental impact are also major considerations. The mass a soldier can carry on a mission is already approaching its limits forcing a trade-off of bullets or food for batteries to power electronics (NRC, p. 28).

Mobile Platform Energy Systems combine the propulsion and electric energy generation functions. In the future, mobile platforms may benefit from integrating the power system to include power for weapons and for propulsion (mobility) and other vehicle electric functions. With careful planning and a well-thought-out control strategy, a central power system may feed the continuous, transient, and pulsed loads while reducing the platform size and increasing the efficiency. Developing technologies are going to enable the military to move toward replacing heavy, inefficient systems with more efficient "more electric" platforms. Critically developing technologies are essentially converging towards all-electric vehicles. Currently, some commercial hybrid vehicles, primarily transit buses, are being made in quantity. In the United States and Europe, several programs have made prototypes or electric or hybrid-electric military vehicles, and some are even being tested.

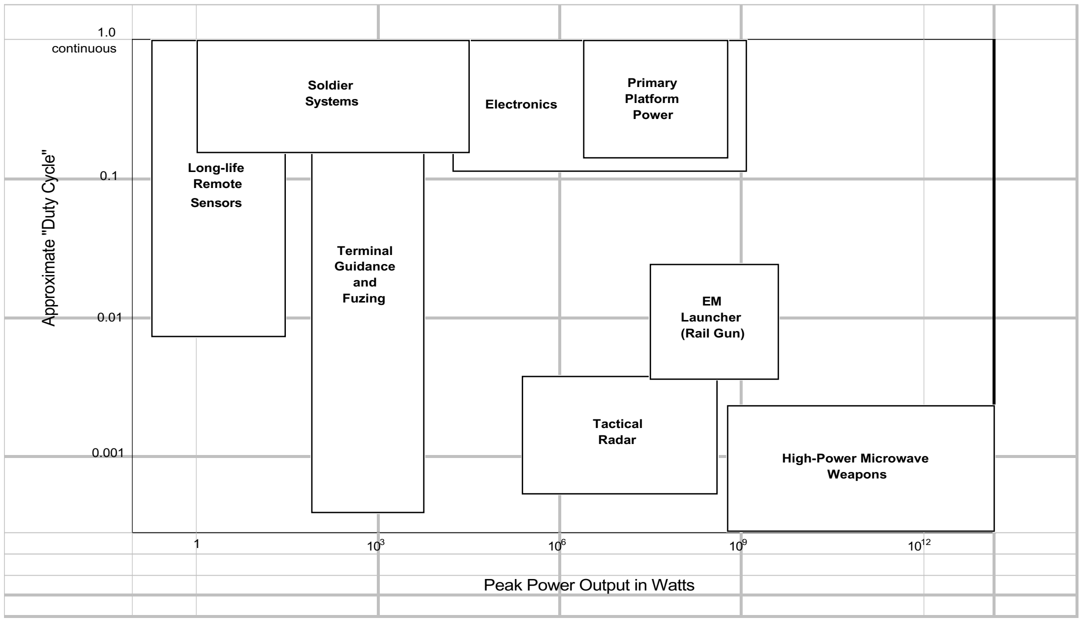


Figure 7.0-3. Peak Power and Duty Cycle for Pulsed and High-Energy Systems and CW Energy Systems for Several Applications or Missions (Adapted From ATAR)

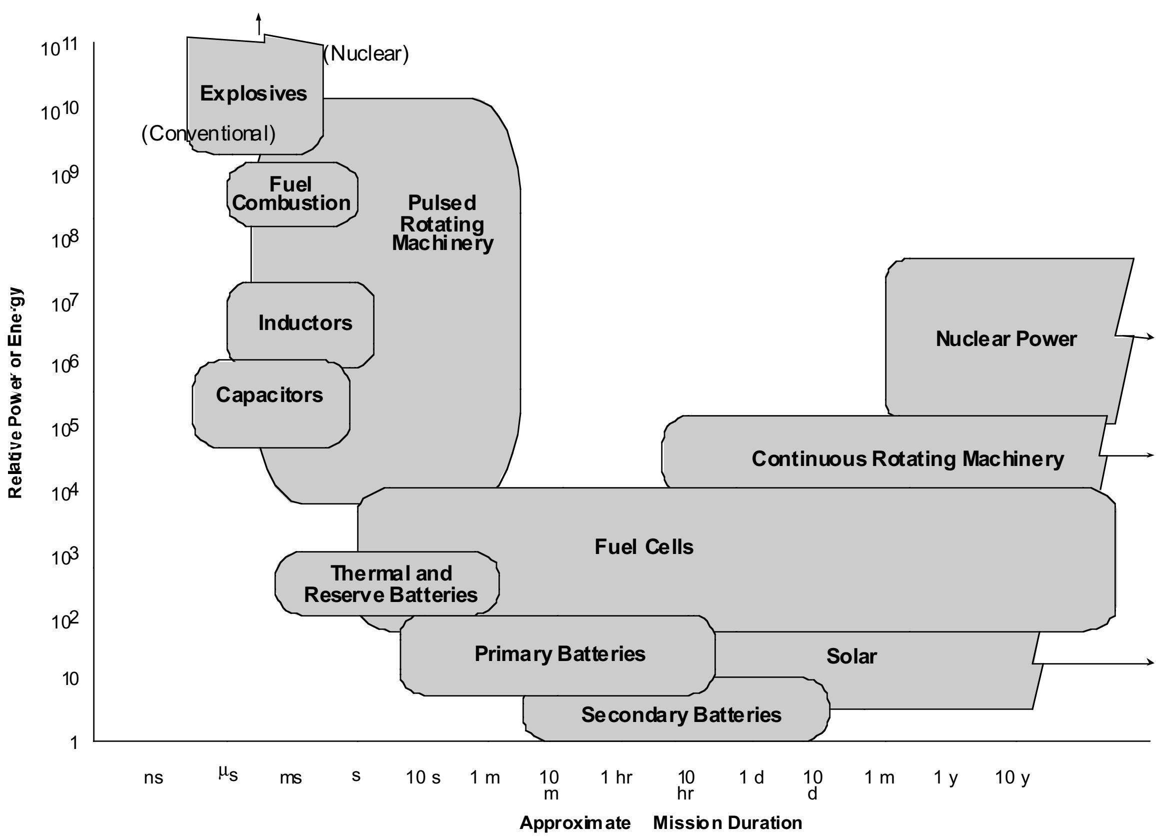


Figure 7.0-4. Trends in Discharge Times of Power System Technologies (Adapted From ATAR)

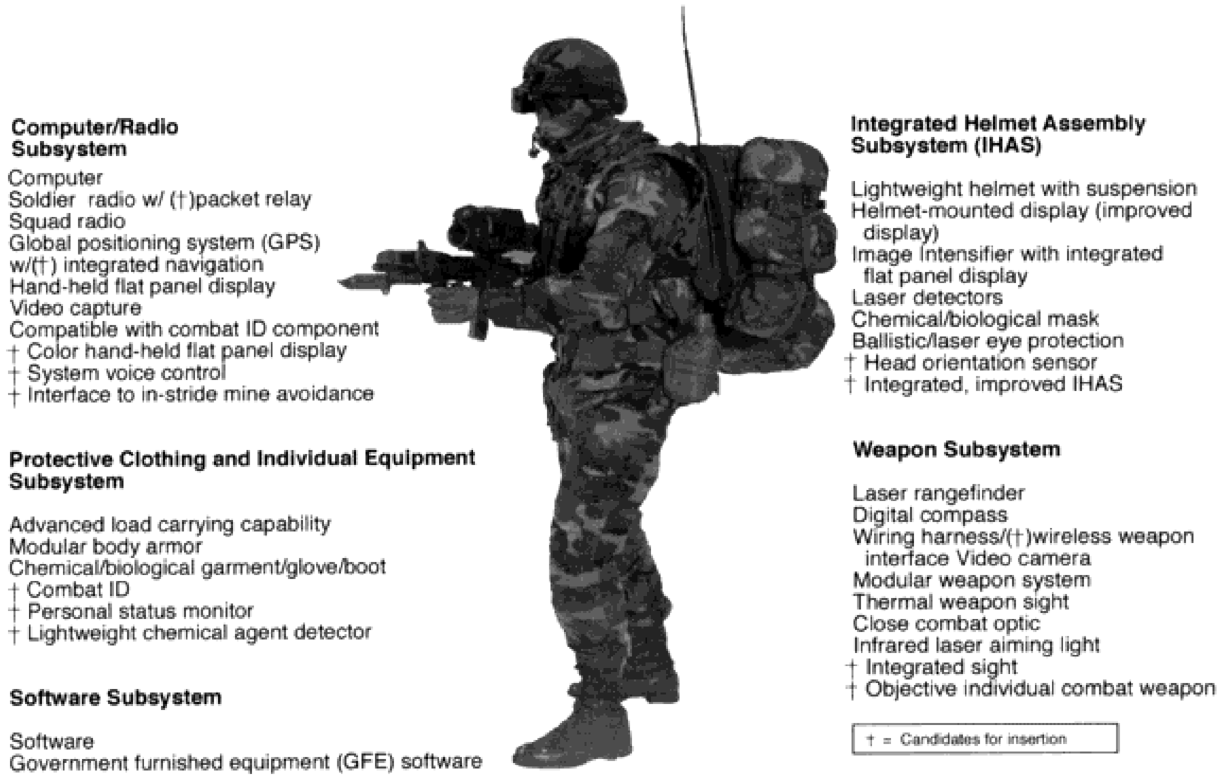


Figure 7.0-5. Sample Power Requirements of Soldier Power Systems (Source: NRC, 1997)

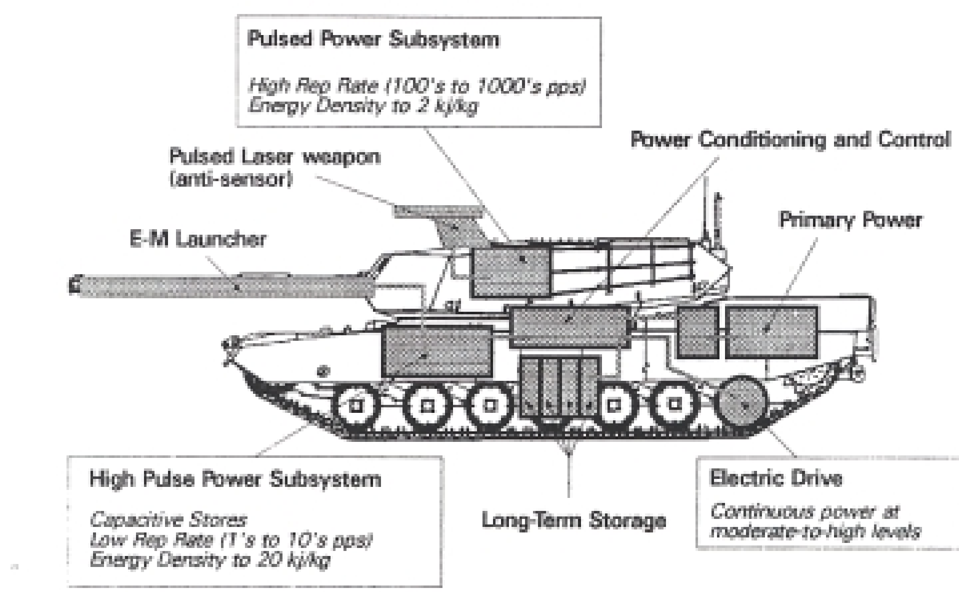


Figure 7.0-6. Advanced Hybrid Ground Vehicle (Source: ATAR)

BACKGROUND

To create useful power, energy is converted from potential to kinetic and either stored or conditioned and then delivered to a load. This power can be provided continuously or in pulses. Varying military applications require power to be delivered in time periods ranging from extremely short durations (on the order of nanoseconds, 10^{-9} sec) to continuous duty. Specifically, many specialized advanced weapons require pulsed power. Power electronics and other components used in continuous systems have very different characteristics from those used in pulsed systems.

Not only are the materials and component advancements in energy systems key, but design philosophies are essential for delivering a product in the most efficient and affordable manner. The approach of Synchronizing Enabling Technologies (SET) is the assessment and the development or implementation of enabling technologies to support a thrust area. It is analogous to knowing the ingredients for a recipe and timing their preparation and introduction into the amalgam. To be successful, a proper assessment of needed enablers should be completed during the early phases of a technology's development. Enablers can range from parallel developments to components or materials, such as composites, that are in the research and testing phase. Synchronizing technologies is an important management issue that will be reiterated further in relevant technology areas.

Soldier Systems

Soldier Power Systems (see Figure 7.0-5) will provide the 21st century warrior with power sources that are enabling for a host of man-portable electronic devices ranging from communications and sensors to weapons. The warfighter will be the keystone of the future digitized Army. Power requirements have been estimated as high as 500 W, with 22.9 W as the current power assessment for the (Army) approved Land Warrior system (NRC, 1997).

In the far term, nuclear power and rotating machinery (microturbines) offer choices for soldier power. Nuclear power has not yet come to practical design because of significant system-implementation issues associated with radiation near biological tissue and social feelings towards ionizing radiation. The specific energy of radioisotopes, however, which can be greater than 100 MW hrs/kg, combined with more efficient energy converters, could easily solve power-generation issues for the unmanned future soldier. Continued efforts may also see other power technologies come into use for the infantry. Such technologies include biological energy sources (for milliwatt applications) and advanced capacitors and converters.

Mobile Platform Energy Systems

Mobile military systems combine the prime propulsion and onboard electrical power-generation functions. The net effect is an energy system that has operational advantages of reduced signature, increased energy density, lower weight and volume, greater flexibility in configuration, and greater economy/reliability. Electrical energy components are characterized by a significant reduction in moving parts, the elimination of rigid connections, and an improved ability to use small and irregular spaces within a vehicle. Potential application areas for migrating to a more-electric drive include:

- Active suspension
- Active protection
- Drives
- Computations
- Motor controllers and electric filters
- Actuators
- Weapons
- Sensors.

Energy systems for all types of combat vehicles are broadly characterized by the level of energy required and the time over which the energy is demanded (pulsed or continuous). Components of the platform's energy system include an engine-generator, which is sized to meet the average energy requirements of the vehicle. (This is not always true, however, especially in critical military systems that must be redundant and survive battle damage.) Coupled to this are the energy-storage and energy-management components that make it possible for the system to meet the peak energy demands required in mission execution. Energy density, thermal management, cost, and packaging are critical parameters for military energy systems. Aggressive management, combined with deliberate restraint of system designs to those that satisfy required parameters, will be essential to producing economical, reliable, and high-performance systems. Thermal and electromagnetic capability (EMC) properties will remain essential design and performance parameters.

Electronic Packaging And Thermal Management

Some of the major considerations in the Soldier Power and Mobile Platform Energy Systems are electronic packaging and thermal management**.** The method by which components and assemblies are integrated play a vital role in the performance and reliability of an end product. Some of the major advances in power technology—both in performance and in cost—will be the result of electro-mechanical-magnetic packaging. Packaging occurs at all levels of product development. Because it is ubiquitous, the following definition indicates how it is used in our discussions: Each level in the electronics hierarchy has within itself the combining of parts to make an assembly. For example, a semiconductor has a die, wire, housing, and leads to form a component. The manner in which these parts are put together is called packaging. Packaging mainly involves thermal management, structural integrity, interconnections, and electromagnetic compatibility. We can apply this same example to each level of assembly in an electronic system (e.g., begin with components and then move to subassemblies, power supplies, DC-DC converters, and functional systems). Finally, when all these parts are integrated together (system packaging), the result is an end product.

One of the revolutionary new packaging approaches is to integrate individual components into each other to form a new component that has increased functionality, lower cost, and higher reliability because of reduced interconnections. An example of this is integrating resistors and capacitors into the internal layers of a printed circuit board. This results in greater packaging density, lower cost and reduced interconnection (compared with discrete components) and, thus, higher reliability. Another example would be integrating semiconductor dies directly into magnetic assemblies, such as a transformer. This is a new approach and will have a profound impact on discrete component manufacturers as the technology matures. For example, if capacitors were directly embedded in a printed circuit board, the demand for discrete capacitors would be less. Understanding the physics and manufacturing processes needed in this functional integration is critical for making significant advances in packaging.

Electronic packaging is a rapidly advancing technology that has been fairly dormant for many years. While advanced electronic packaging techniques have been developed in microelectronics, little significant work has been done in the higher levels of the interconnect hierarchy (subsystems and systems packaging). Packaging, with respect to power systems, must be viewed from an end-use perspective in order for the system to be efficient and effective. This is becoming more important with the introduction of integrated functionality, where multiple discrete components are being integrated and built as a new discrete component. Advanced packaging is critical for meeting the demands of efficiency, thermal management, and power density in future power systems. Integration at all levels will be needed, including interconnections such as direct die attach technology.

To illustrate, capacitors and magnetics are critical components that require improvements to meet the new packaging demands. Further, high-temperature and high-efficiency power semiconductors are also important component needs. In all cases, necessary technological advances include the materials and processes used in building such components. Advances in thermal management will come from heat spreaders and selective cooling approaches.

In cases where integrated functionality is used, hybrid test equipment will be needed to evaluate the parameters and characteristics of multiple components in one (component). High-technology processing equipment will also be needed for areas previously satisfied by lower technology processes.

Education and establishing a systems-level packaging mentality are the main issues in evolving to advanced packaging capabilities. Change is required to overcome the headset of single-level packaging. Effecting this change will be difficult because of the subsystem mentality that exists and the way parts are designed and manufactured in today's environment.

Power technology has moved forward in the last several years at a fairly rapid pace, although, in general, it has not moved nearly as fast as it has within the semiconductor industry. This difference in sector performance is evident across the military and the industrial communities. Many of the packaging demands for higher density, higher performance, lower weight, and lower cost power systems are common to both areas, especially in the area of more cost-effective semiconductors. The comparatively large physical size of power system components, compared with the rest of the electronic package, has inhibited system density improvements. Reactive components tend to be large, heavy, and inefficient. Spatial compression of these components produces increased power density (W/cm^3), without decrease of thermal impedance, resulting in localized heat build up.

Semiconductor design philosophies can be extended to high-density power converters and to regulators, where system packaging is critical. Proper partitioning, with special attention given to electromagnetic interference and thermal management, will be needed. Thermal management will enlist a combination of active and passive cooling technologies to control “hot spots.” Thermally conductive materials will play a bigger role in thermal management, with “heat spreading” being used to a larger degree. Systems packaging will require the integrator to understand clearly each subassembly and how it will affect system performance. The application of high-density power regulators into the systems architecture will be key to enhanced system performance.

Integrated Functionality

An area that is emerging from the packaging discipline is Integrated Functionality. The role of the packaging engineer is to integrate components into a functional assembly using processes and assembly techniques made available to the manufacturer. This in itself may be viewed as integrating functionality; however, it is also starting to emerge at a lower level. This function actually involves the discrete components, such as resistors, capacitors, and semiconductors used in assemblies. We call this integrating functionality at the component level. The result of this activity is the creation of new components that contain the collective features of multiple components (see Figure 7.0-7). This change is profound since it will change the supplier base to the power supply industry. The rationale behind the development of integrated functional components is increased reliability, better performance, space reduction, and cost benefits—features that are desired in power product development programs at all levels.

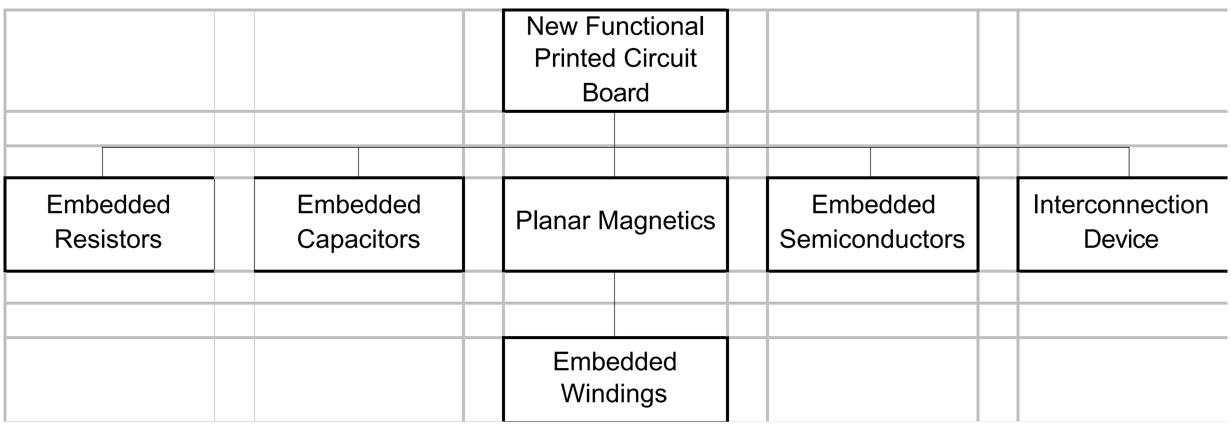


Figure 7.0-7. Example of Integrated Functionality

The challenges in integrating the functionality of components are significant but can result in major advances in end-product cost and reliability. For example, to be able to combine the desired features of multiple components, a good understanding of the individual components is necessary. This includes understanding the way in which the components are manufactured and knowing their constraints. With this knowledge, combining features of multiple components into one part can, in many cases, become a reality.

An example of integrated functionality can be seen in planar magnetics. This is where the windings for the magnetics are incorporated in the printed circuit board using etched circuit traces. The core material is inserted in holes or slots in the printed circuit board and bonded, to complete the magnetic assembly. This operation, in essence, replaces a discrete component. It also eliminates the core winder and creates a more functional printed circuit board. It takes manual labor out of the winding process, which, in turn, will improve cost and quality. The printed circuit board manufacturer is developing new skills in producing planar magnetics, but these new skills do not significantly affect the manufacturing process. A result of planar magnetics is the elimination of a discrete component in the overall assembly, which, in turn, increases reliability. The business ramification is a reduction in purchased magnetic assemblies. Eliminating the need for particular discrete magnetic components takes a certain amount of business from the transformer companies but also provides some packaging flexibility by core geometry selection, especially in low-profile applications.

While this change had little affect on the printed circuit industry, other component integrations will have a profound impact. An example is the emerging technology of embedded capacitors. Significant reductions to the size of a power supply can be realized by replacing discrete capacitors mounted on the printed circuit board by embedding capacitors within the layers of a printed circuit board. As new dielectric material technology with high-energy storage features becomes available, a breakthrough in power density could result. This integration would have a large impact on printed circuit board manufacturers. They would be building a capacitor(s) into their boards, thus becoming a manufacturer of an electronic component and an interconnection component. This would involve enhancing the knowledge base of printed-circuit people in many areas. They would be required to learn new manufacturing processes and deal with new materials and would have to be able to test their embedded capacitors. They would require much of the knowledge of capacitor manufacturers. This would be like building a capacitor without a package (as in a discrete component). Terminations of the capacitor would be included in circuit traces and plated through holes. The new processes that will be needed to build this product presently exist in the semiconductor and other industries and can be easily transitioned. The equipment required would include vacuum deposition equipment. Although the printed circuit business will change, the financial rewards could be huge. The power supply industry desperately needs higher power density and the replacement of discrete capacitors. Capacitors currently consume about 20 to 30 percent of the volume of a power supply, depending on the type of power supply. Capacitors also account for about 20 percent of the cost of a power supply. This could be a very lucrative new business. However, again, there are business ramifications. New capital equipment purchases would be needed and the labor force would have to be trained. This “new component” will affect the discrete capacitor manufacturing companies by decreasing the need for discrete components.

Other examples of integrated functionality have also had an impact on power electronics [e.g., application-specific integrated circuits (ASICs)]. ASICs have replaced many discrete components with a single package. Before ASICs, many electronic circuits required several discrete components to provide a certain function, such as housekeeping circuitry for sensing power supply functions. Some standardization was developed and ASICs became very practical devices. Replacing several discrete components with a single component that has the reliability of an integrated circuit has had a large effect on power supply reliability. A mean time between failure (MTBF) of over 1 million hours for a DC-DC converter is not unusual today. Much of this improvement can be attributed to integrated functionality and improved designs.

Direct die attach technology is another area being used more frequently. This eliminates a level of interconnection and can increase power density and improve reliability.

Other designs that demonstrate additional ways of integrating functionality (by combining parts and reducing the amount of interconnections) will soon be introduced to the market. This interesting trend will have a significant impact on today’s discrete component supplier. Suppliers that today sell discrete components must become involved in this activity if they want to preserve their markets or open new markets.

Improvements from military mobile systems with integrated functionality include:

- Simplicity
- Permanent magnetic materials
- Reliability
- Efficiency
- Operating temperature
- Power density
- Thermal management
- Energy extraction.

Electromagnetic Compatibility (EMC)

When dealing with electromagnetic emissions, two important considerations are conducted emissions and radiated emissions. Conducted emissions are generally managed with in-line electromagnetic interference (EMI) filters. Radiated emissions usually require containment with ferrous metal materials and shielding design approaches to eliminate radiation. Shielding materials would include products such as fingerstock and braided mesh for seams and doors or ports to the electronic equipment.

High-Energy Density Conventional Systems

High-density conventional systems will be used for many applications in mobile platforms. High-density conventional systems are those comprising components/subsystems rated at less than 500 kW. Such systems are found in almost every military operating system, including multiple components of major weapons. Critical technologies in this section cover both energy sources and power-conditioning activities. Energy systems are fundamental components, which are often specifically tailored for each of the other major technology areas within the list of Military Critical Technologies (MCTs).

Technologies for components or systems rated at less than 500 kW are migrating toward revolutionary changes in energy density and precision. This is critical to the military because of the needed improvements in system performance: new capabilities are becoming possible. Power system miniaturization is an important element and has led to micropackaging on a chip and distributed packaging to perform a function such as track motor or flight control. In the near future, many weapons systems that now commonly use mechanical, hydraulic, or pneumatic components will rely on electrical systems. Major initiatives include the More-Electric Aircraft, All-Electric Ship, and the Future Combat Vehicle (Army). Military requirements for energy systems are distinguished primarily by the need for ruggedized packaging, and high-energy and high-power densities. Thermal stress is the primary concern, with shock stress an important secondary regard. Thermal management or components capable of functioning at high temperatures are keys to reduced failure rates and improved system survivability. Military demand for low failure (total life-cycle reliability) drives new design architectures. As a result, approximately 40 percent of the total demand for military energy systems results in custom-designed applications to fit military systems requirements. Such requirements create pervasive pressures to reduce production and product costs.

High-Density Converters

An example of high-density conventional systems would include high-energy density converters. DC-DC power regulators in the military and the commercial sectors have become smaller and more powerful. One of the driving factors in the military sectors is weight as it applies to a payload. In the commercial arena, this trend has been driven by the fast-moving semiconductor industry. Hardware size in telecommunications, networking, and computer systems has been greatly reduced by the high-performance semiconductors now in the marketplace. Slow to follow this technology trend are the DC-DC power regulators. However, in industry, significant gains have been achieved in reducing of the size and increasing the reliability of DC-DC power regulators. In industry, regulators designed today can be packaged in volumes of 70 to 100 W/in^3 and have a MTBF of over 1 million hours—numbers that would look very much like a military requirement just 5 to 10 years ago. The resulting designs of these high-power density regulators are accomplished by designing new topologies, developing new components, increasing the functionality of components, and mastering electro-mechanical packaging. This is the way to get to high-density regulators. However, as the semiconductors progress to lower and lower voltages and the chip power levels increase, the issues of high current distribution and the associated power losses become significant, putting more difficult constraints on the design engineers.

The National Technology Roadmap for Semiconductors developed by the Semiconductor Industry Association has projected the power supply voltage to be 1.8 V by the year 2001 and down to 0.9 V by the year 2010. The maximum power associated with these numbers is also projected to increase significantly. In 2001, the power at 1.8 V is expected to be 120 watts, and, in 2010, the power at 0.9 V is expected to be 180 W. With this level of chip power density, power regulator designers must consider several strategies.

Power system architecture ranks as one of the most important considerations. With the very-high-power requirements of the semiconductors, one design option is point-of-load power architecture, which means placing the regulator as close to the actual load as possible. This would minimize the power distribution losses. This would also require the designer to view the power supply at the system level, integrating it into the system efficiently. This effort requires the use of advanced systems-packaging designs with careful considerations for thermal management.

Thermal cooling technologies become an important factor in this overall package, and chilled air becomes an important choice, especially in chip cooling.

Another option is distributed power. This approach would locate the power regulators close to the load but not at the point of load. This approach would use larger regulators that provide power to more than a single chip. The problem of power losses caused by the high current levels is addressed with power bussing techniques. The interconnection design must receive careful consideration. To minimize power losses, hard connections, such as bolted on bussbars, would be preferable to removable connectors. An advantage of this power architecture is that the approach will easily accommodate *n+1* redundancy. This configuration provides an extra regulator paralleled with the primary regulators. If a regulator fails, the extra regulator will automatically be activated. This will afford the overall system higher availability and will appear to the user as increased reliability. If current sharing is being used with the paralleled regulators, actual reliability is increased because of the reduced loading on the individual regulators. This approach is possible but not nearly as suitable as the point-of-load power architecture, since it would take up real estate that is not readily available and would not be as cost effective.

TECHNOLOGY ASSESSMENT

Table 7.0-1 highlights technology groups, their function and relevant waveforms, and some applications where they may be found. Figure 7.0-8 compares the relative parameters of power electronics.

Table 7.0-1. Technology Groups and Their Functions (Adapted From ATAR)

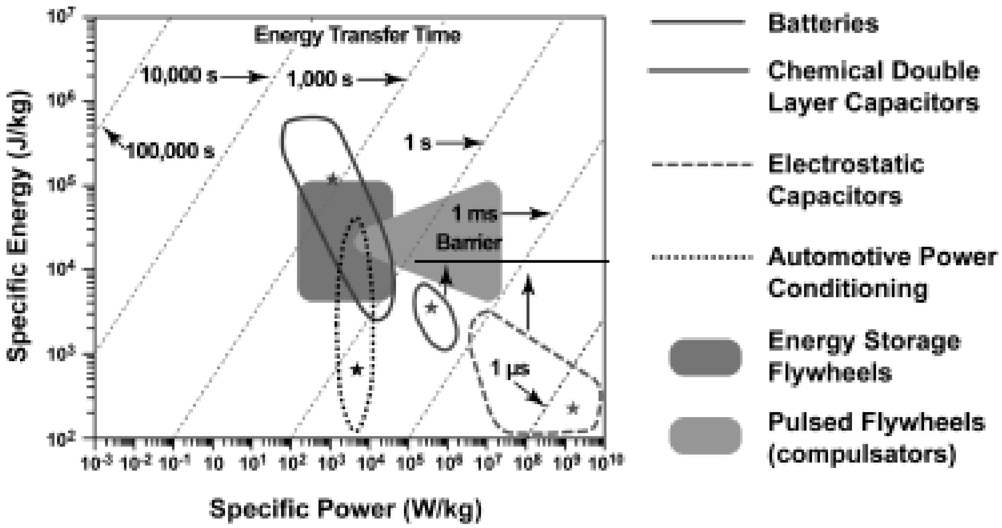
ENDURING TECHNOLOGY GROUP	GENERATION & CONVERSION	STORAGE	POWER CONDITIONING	SOLDIER SYSTEMS	COMMUNICATION	COMPUTERS	ELECTRIC VEHICLES	STEALTH	HPM	DIRECTED ENERGY WEAPONS	ELECTRONIC WARFARE	RADAR	ACTIVE PROTECTION	NUCLEAR EFFECTS SIMULATION	LASER WEAPONS	RAIL GUNS
Batteries	CW, P	CW, P		X	X	X	X	X		X	X	X				
Fuel Cells	CW, P			X	X	X	X	X								
Capacitors		CW, P	CW, P		X			X	X	X	X	X	X	X	X	X
Switches	P		CW, P		X		X		X	X	X	X	X	X	X	X
Rotating Machinery	CW, P	CW, P	P	X			X									X
Inductors		CW, P	P						X	X			X		X	X
	FUNCTIONALITY			MILITARY APPLICATION												

CW = *Continuous*
P = *Pulsed*

Batteries

A battery is a device that converts chemical energy to electrical energy. The two types of batteries are primary and secondary (rechargeable). Batteries are desirable because of their reduced thermal and acoustical signature, ability to be molded into many configurations (mission specific), portability, and ability to store energy at high densities. Table 7.0-2 displays the status of the North American military battery industry as of 1994.

Battery design and fabrication is a proprietary, art-intensive activity in which details of know-how are closely held and protected. Factors of particular interest include high-temperature materials; high-conductivity electrolytes; the selection, refinement, and use of specific catalysts; electrode design and fabrication; packaging (especially corrosion and safety seals); additives for electrodes and electrolytes; and flexible small-lot manufacturing



- High peak power at ***high efficiency***
- Current technology illustrated by ⋆

Figure 7.0-8. Relative Capabilities in Power Electronics

technology. In addition, the controlled (graceful) degradation in performance over time—as opposed to a sudden catastrophic failure—is a very desirable military trait. Figure 7.0-9 displays the inherent tradeoffs in battery technology. Increasing stored energy comes at the expense of power performance—with one caveat: For traditional battery construction and electrochemistries, an apparent trend indicates that a single battery is typically not able to provide both high power and high energy efficiently.

Table 7.0-2. Status of North American Military Battery Industry by Chemistry (Source: NATIBO)

Chemistry	Military/ Commercial Demand	Present Supplier Health	Base Health	Projected Business Climate	Convertibility
Thermal	Medium military demand. No commercial demand. Potential for emergency power systems in commercial.	One healthy supplier. Others considering entry.	Healthy.	Stable and flat.	N/A.
Lithium	Military demand for lithium sulfur dioxide decreasing. Increased military interest in other lithium chemistries. Small commercial demand. Commercial demand for lithium ion and lithium polymer increasing.	Five companies with poor-to-good health.	Diversification from military to commercial market is a concern because of a rapid military decrease and a slow commercial increase. Military transition to lithium maganese dioxide should support at least two suppliers. Suppliers looking for commercial market to sustain business.	Need product diversification based on increased commercial demand.	Lithium sulfur dioxide to be replaced by lithium maganese dioxide. Lithium thionyl chloride dual use today (bobbin configuration). Lithium ion dual use for future.
Mercury	Military demand decreasing. Small, niche commercial demand.	Presently stable. Eventually supplier will disappear.	Not required.	Market going away.	N/A.

Table 7.0-2. Status of North American Military Battery Industry by Chemistry (Source: NATIBO) (Continued)

Chemistry	Military/ Commercial Demand	Present Supplier Health	Base Health	Projected Business Climate	Convertibility
Silver	Mostly military demand. Some commercial demand.	Four suppliers with fair-to-good health.	Healthy. Silver cadium going away.	Stable, but overall demand decreasing.	N/A.
Lead Acid	High commercial demand. Piggyback military applications. New commercial applications for the future.	Four healthy suppliers.	Healthy.	Excellent and expanding.	Full convertibility and dual use.
Nickel Cadium	High commercial demand. Piggyback military applications.	Three healthy suppliers.	Healthy.	Excellent and expanding.	Full convertibility and dual use.
Magnesium	Small military demand. Small commercial demand.	Two healthy suppliers.	Healthy.	Stable and flat.	Army uses dual-use batteries. Navy does not use dual-use batteries.

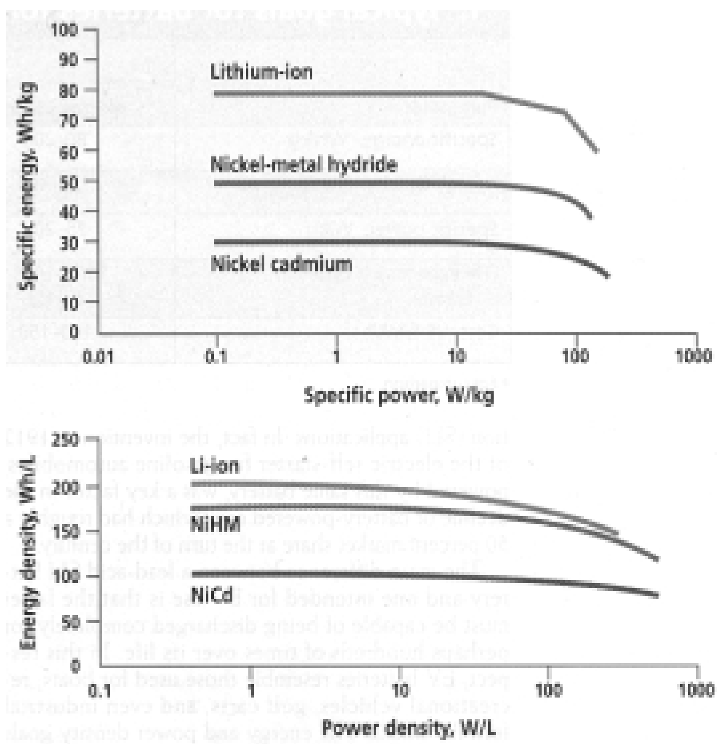


Figure 7.0-9. Tradeoffs in Battery Technology (Source: IEEE, Nov. 1998)

Fuel Cells

"A fuel cell is a continuous-feed electrochemical device of limited pulse power capability" (ATAR, p. II-14). It produces electricity by oxidizing hydrogen. Fuel cells are categorized by the electrolyte that is contained within them and by their operating temperature. Air or oxygen is used as the oxidant, and hydrogen or hydrogen derived from a carbonaceous fuel is used. (Hydrogen is the simplest fuel from an operational viewpoint, with increasing difficulty in consuming more complex fuels from methanol through diesel.) However, storing hydrogen on the battlefield is difficult because it needs to be maintained at near absolute zero temperature and is a formidable fire hazard. Present systems require that such hydrocarbon fuels be reformed or partially oxidized to yield hydrogen. Current smaller (200–300 W) systems are anticipated to use hydrogen and, subsequently, methanol as a fuel. For small power source applications, direct methanol fuel cells will emerge early in the next century (about 2005). Although hydrogen is a difficult logistics issue, it can supply more kilowatt-hours per kilogram than other fuels (see Table 7.0-3).

Table 7.0-3. Specific Energies of Various Fuels (Source: NRC, 1997)

Fuel	Specific Energy (kW-hrs/kg)
Hydrogen	33.3
Gasoline	12.2
Diesel	11.9
Methanol	5.5
Propane	12.8

Fuel cells that can use diesel JP8 fuel are of special interest to the military since these fuel cells would reduce the logistics burden of supplying multiple fuel types to the battlefield. This requires a reformer, however, to process the fuel before it is used.

As electric vehicles (EVs) and high-technology, low-weight, electrically powered devices expand in number and importance, the market for fuel cells is likely to expand rapidly. All fuel cells have tradeoffs. The advantages: they are lightweight; have high energy output, significantly reduced thermal and acoustic signatures [e.g., proton exchange membrane fuel cells (PEMFCs)], cogeneration abilities, and clean operation (primary byproduct being water; and are very durable. The disadvantages: they are expensive, occasionally inconvenient, and sensitive to air-borne contaminates. Most scientists believe that these problems will be solved relatively quickly as research and development (R&D) proceeds in this area. Early in the next century, fuel cell costs should approach U.S. $50/kW and be more competitive with internal combustion engines.

Among the vehicular applications for fuel cells are spacecraft, aircraft, industrial, automotive, ship, and submersible vehicles. Of these, only spacecraft and submarine applications have reached the commercial stage. Industrial and automotive applications are in the near-commercial and R&D stages, respectively. Ships and aircraft powered by fuel cells are the applications that are furthest from the market because they are still in the conceptual stage. Ballard of Canada has developed small fuel cells for possible use in manpack radio sets and laptop computers. Fuel cells are still in the early phases for battlefield usage. Currently, only PEMFCs demonstrate practical applicability for soldier power. Figure 7.0-10 forecasts the average power for fuel cells. These data represent the maximum demonstrated power of the largest fuel cells.

Fuel cells are also being tested for electrical power for buses, cars, and other vehicles. Many prototypes currently exist. Among the military applications for the fuel cell are EVs and the Soldier Integrated Protective Ensemble (SIPE), both of which would provide more power and less weight for the vehicles and man-portable units.

Another application for large-scale fuel cells is prime power generation. Fuel cell power plants have been developed and are being used in several remote areas to generate power for small communities. Moreover, fuel cells have been used in large-scale cogeneration applications, where they produce heat and electricity for buildings. This is possible because fuel cells generate a great deal of heat during operation. As fuel cells become more commercially available, they are expected to take a significant market share from batteries because of their greater power and

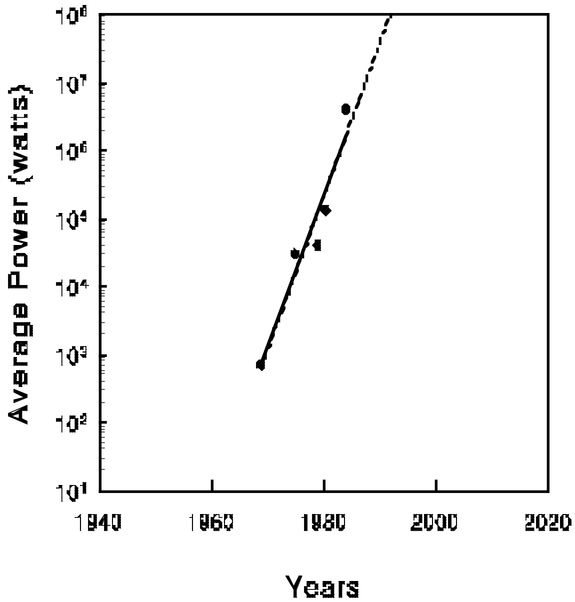


Figure 7.0-10. Fuel Cell Average Power Forecast

lighter weight. The final size of the market for vehicular fuel cells will be determined by the developers' ability to decrease the cost-per-watt of energy. As the cost for the fuel cells is reduced, the market will grow. Commercial production of automotive fuel cells is expected by 2005, and production over 100,000 units per year by 2010.

Capacitors

Capacitors (see Figure 7.0-11) are a basic component for energy storage and power conditioning in a variety of pulsed and continuous applications. Areas of application include filters in alternating current (AC) and direct current (DC) systems, AC resonant-charging power supplies, switched-mode power supplies, energy storage system, and high-frequency bypass circuitry. Major types of capacitors are usually described by their insulators, such as polymer, ceramic, chemical double layer (CDL), electrolytic, and mica (see Figure 7.0-12). Performance depends upon the usage (burst vs. continuous), the duty cycle, and the amount of energy or charge transferred. The major technical problem involves developing new dielectric materials and the related manufacturing processes to produce very-high-energy density capacitors that will operate at very-high-power levels.

Capacitors have wide applications in consumer electronics, telecommunications, computers, medical instruments, aircraft, spacecraft, robotics, and automobiles in the defense and the commercial sectors. These applications determine the performance of the capacitor market. For example, if a country has a strong consumer electronics sector in its economy (such as Japan), the capacitors found in those types of applications are going to perform particularly well. Most of the capacitors being manufactured are for small electronic devices, primarily consumer oriented. The economic forces affecting these devices are well known, and there is a wealth of market data available.

The economic forces affecting the consumer market are quite different from those affecting the capacitors of interest to this analysis. Capacitors capable of very-high-energy density at very high power are a special subcategory, and little economic information is available since this is such a specialized market. However, certain comparisons can be made. Capacitors, in general, are following the trend in semiconductor technologies: components are getting smaller, lighter, and more powerful. Greater amounts of capacitance are being fit into the same or smaller sized packages. These developments have compelled manufacturers to keep up with industry demands, and these demands have created pressure on the manufacturers to make huge capital expenditures on manufacturing equipment so they can produce state-of-the-art technology. This causes a market consolidation. Firms who cannot maintain these

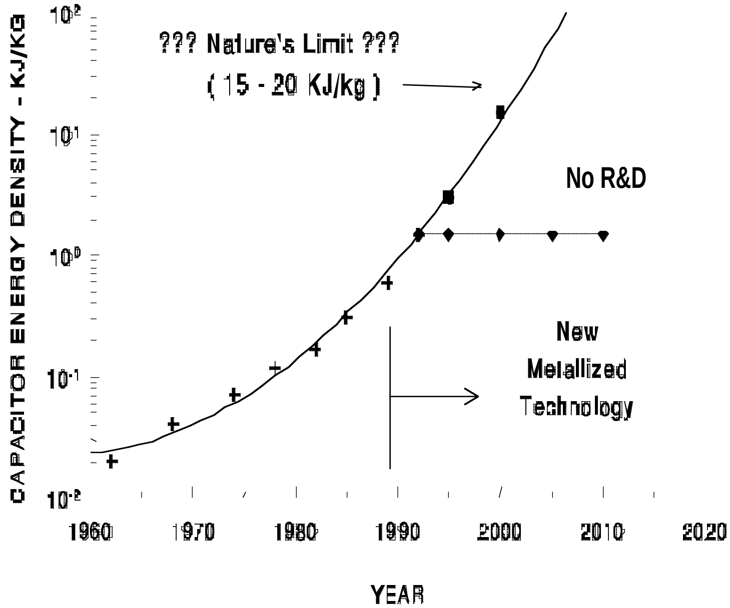


Figure 7.0-11. (High-Energy Density) Capacitor Technology Forecast

Note for Figure 7.0-11: *The diamonds represent a future without R&D in capacitors, while the squares identify an extrapolation with continued R&D.*

expenditures either fold, get bought out, or find a niche where they can remain solvent. Consolidation has occurred mostly in the capacitor market, and those firms who are present and functioning in the market will most likely continue be a factor in the future.

Ultracapacitors (also known as supercapacitors and CDL) are emerging as viable energy storage devices for hybrid-electric vehicles (HEVs), uninterruptible power supplies (UPS), and automotive and aircraft ignition systems. Presently, France, Germany, Italy, Japan, and Russia have active ultracapacitor research, development, and engineering (RD&E) programs. HEVs with ultracapacitors have been demonstrated in France, Italy, Japan, and Russia.

Several foreign countries produce high-quality capacitors for the electronics industry (France, Germany, Japan, Russia, and the United Kingdom). The United States is the world leader (based on energy density, W hrs/kg) in high-power capacitors, especially those suited for the very-high-pulsed-power applications needed by the military. Maxwell Labs and Aerovox are the two leading manufacturers. In addition, Martin Marietta, General electric (GE), and some smaller companies (Power-One, Giner, Pinnacle Research, Evans) are involved in certain types of special-purpose high-power or high-density capacitors.

Filtering applies to mainly AC ripple suppression in DC bus and power transmission systems. The specific capacitor technology employed is application specific and dominated by ripple frequency. In some applications, large fractions of the stored energy are removed from the capacitor during some portions of the mission, making the capacitor internal losses a dominant consideration in applicability and efficiency.

Switches

Switches are *critical* components for high-power conditioning and pulse formation. They are mainly used in networks designed to convert power from one form to another. A switch's internal environment can be solid state, gas, magnetic, or liquid. The driving requirements in switch technology are high efficiency (greater than 98 percent), negligible internal inductance (<< 1 nH/A), and increased operating temperatures (–55 through +500 ºC desirable). The latter is being realized through Silicon Carbide (SiC) switches, which are an emerging approach to the temperature problem. Applications are motor control systems, UPSs, power conditioning, high-voltage DC

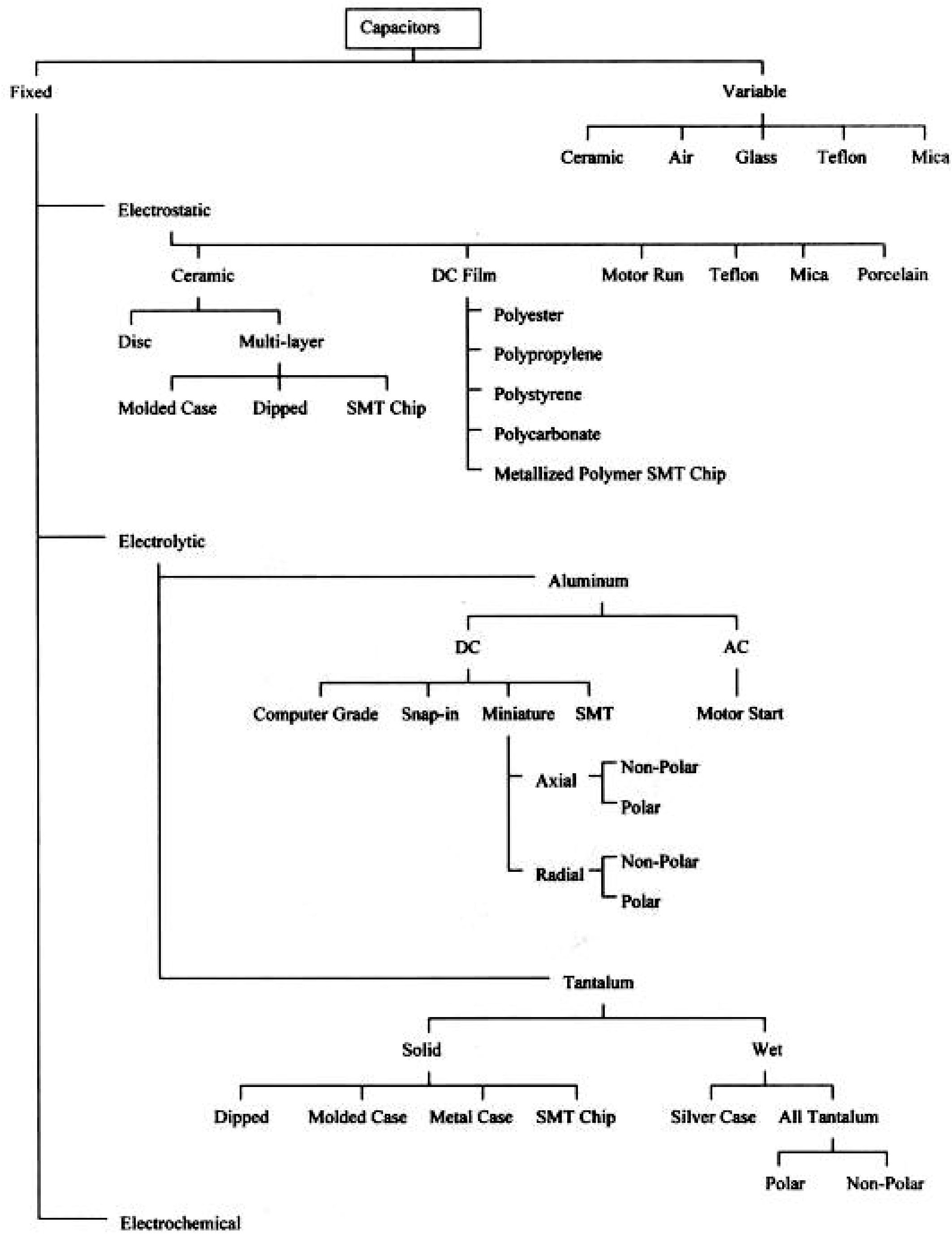


Figure 7.0-12. Types of Capacitors (Source: Mallory Capacitors)

transmission, inductive heating, and many other commercial applications. Figure 7.0-13 compares voltages and speeds for various switches, and Figure 7.0-14 highlights the trends for several switches.

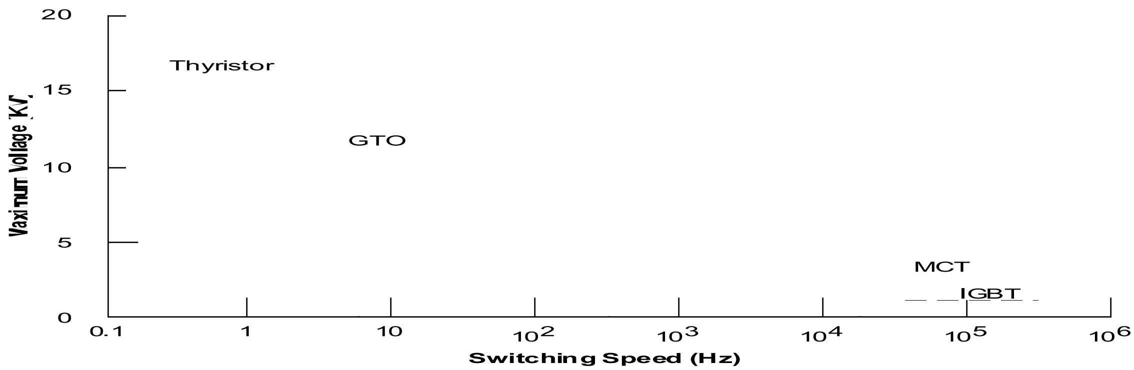


Figure 7.0-13. Speeds for Switching Devices (Source: ATAR)

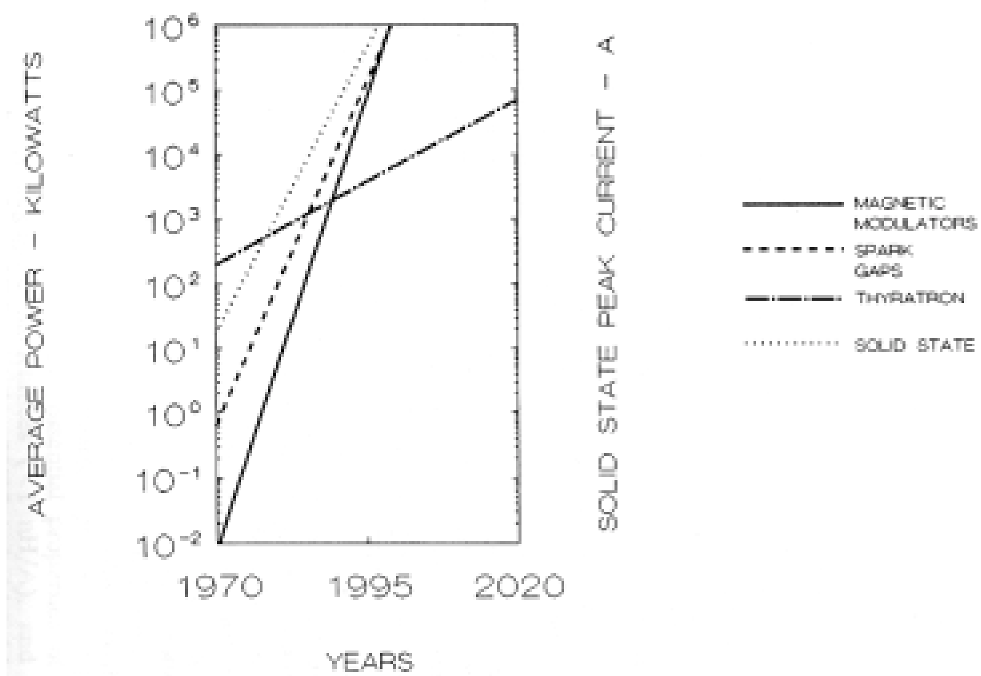


Figure 7.0-14. Trends for Switching Technology (Source: NRC, 1993)

In establishing operating parameters of high-energy switches, care must be taken to avoid subjecting the device to conditions that are potentially capable of causing a fault. For the SCR [Silicon Controlled Rectifier] switch, a fault is a catastrophic event. The spark gap and the triggered vacuum switch, however, regain most, if not all, of their capabilities after a fault. A fault can also cause damage to the overall system as well as the loss of the effectiveness of the shot or the shot itself (H. Singh et al. 1999).

Rotating Machinery

Rotating machines offer the potential for storage and generation of electrical energy. The key requirement is a reduction in size. The Department of Defense (DoD) is interested in several types of rotating machines various pulsed and continuous applications. These applications range from electromechanical energy storage systems using flywheels to high-power density alternators and generators for power generation. Measuring the size of the rotating machine market depends upon what type of device is being explored. Many different devices are referred to as rotating machines, including various motors, generators, and flywheels.

The market for the EV application of a rotating machine is likely to expand quickly. California has enacted a series of strict emission laws that require all car manufacturers to produce zero-emission vehicles by the early 21st century. Among the technologies being introduced to meet these deadlines, the most viable seems to be the EV.

WORLDWIDE TECHNOLOGY ASSESSMENT (See Figure 7.0-15)

Foreign capability will not necessarily follow the same progression as the United States. Culture and diverse needs may be factors that affect developing technologies in different nations.

An extensive list of global fuel cell developers can be found at http://216.51.18.233/fcdevel.html .

Country	Section 7.1 Energy Conversion and Power Generation	Section 7.2 Energy Storage	Section 7.3 Power Conditioning	Section 7.4 Biological Energy Systems
Australia	●	●	●●	
Canada	●●	●●●		●●●
China	●●●●	●●	●●●	●●
Finland				●
France	●●●	●●●●	●●●	●●●
Germany	●●●●	●●●●	●●●●	●●●●
India	●	●	●●	●
Ireland	●●●		●●●	
Israel	●●●	●●●	●●	
Italy	●●	●●	●●	●
Japan	●●●●	●●●●	●●●●	●●●●
Norway				
Russia	●●●●	●●●●	●●●●	●
South Africa	●	●	●●	
South Korea	●●●		●●	
Spain	●			
Sweden			●●●	●
Switzerland			●●●	
Ukraine	●	●	●●	
UK	●●●	●●●	●●●	●●●●
United States	●●●	●●●●	●●●●	●●●●

Legend:
Capability in technology elements Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 7.0-15. Energy Systems Worldwide Technology Assessment (WTA) Summary

SECTION 7.1—ENERGY CONVERSION AND POWER GENERATION

Highlights

- The future battlefield will require systems supplying power at levels ranging from milliwatts to gigawatts.
- Advanced precision weapons, weapons of mass destruction (WMD), radar, and electronics countermeasures and communications systems are enabled through next-generation high-energy electronics systems, including the prime energy sources.

OVERVIEW

Energy conversion and power generation encompass the transformation of biological, chemical, electro-magnetic, nuclear, mechanical, and thermal energy or reactions into electrical power. The output may pulsed, burst, or continuous. The future battlefield will require systems supplying power at levels ranging from milliwatts to gigawatts.

Pulsed power is generated by the inherently pulsed nature of the source, such as explosive technologies, or derived through the use of pulse-forming networks. Further, pulsed sources can be used in conjunction with fast switches to provide pulses of shorter duration, higher frequency, and greater peak power. Burst is a form of pulsed power with the duration between shots (“off”) being much greater than the “on” duration. Continuous power, by definition, is supplied on a continual basis by sources ranging in size from batteries to large turbines.

RATIONALE

All military platforms are subject to volume and weight constraints. In addition, since the ability to initiate actions without awareness by any adversary is becoming more significant, the need for stealthy land, sea, and air platforms is more important. With the exception of hydrocarbon-fuelled air vehicles, all others can be optimized for limited missions using electrical energy.

HEVs and all-electric vehicles will integrate traditional power-generation devices (e.g., combustion engines and generators) with power sources (e.g., batteries and fuel cells). Further, ultracapacitors and batteries have been used with regenerative braking—the process of reclaiming energy through deceleration. All-electric vehicles rely strictly on batteries for power generation, while HEVs combine batteries with other sources of power. Series HEVs use combustion engines or fuel cells to generate electric power and use electric motors to drive the wheels. Parallel HEVs take some of the power from the combustion engine as shaft power and deliver this power directly to the wheels in parallel with the electric motors. These robust platforms eliminate the use of hydraulic, pneumatic, and mechanical power, and the benefits are numerous.

Mobile platforms are important in this discussion because their subsystems require pulsed or continuous power, which is provided by the larger power-generation system. Mobility itself has its own power requirements, which vary with the motion of the vehicle. For example, acceleration requires more power than deceleration. In battle conditions, an HEV would need to provide continuous power to computer, environmental, and low-observable subsystems, radar and mobility. Pulsed power would be required for weaponization [including high-power microwave (HPM), lasers, electronic warfare (EW), and directed energy (DE)], for active protection, and for augmenting propulsion. Mobile platforms include attack vehicles and support vehicles.

Pulsed-Power Generation

Pulsed-power systems are necessary to parts of current and future military systems. Current use ranges from laser range-finders and tactical communication to radars, jammers, and electronic countermeasures. In the future, pulsed-power systems will be critical enabling subsystems for military weapons and other systems ranging from kinetic energy (KE), microwave, and laser weapons to pulsed jammers, mine destruction, and active protective systems. Such particular applications may be powered by a unique combination of the prime power source, energy storage, and power-conditioning and pulse-forming networks.

Continuous Power Generation

Continuous power-generation systems are those ranging from several watts for soldier systems to many gigawatts for EVs. Fuel cells, one source of continuous power, are of interest to all branches of the military because of their low signature, high-energy density, and efficiency characteristics. A significant problem in current fuel cell design is weight because of the requisite pressurized vessels that are heavier than the fuel. While this is not as great an issue for ship platforms, non-electric ground mobility will find more supportability and functionality in internal combustion turboshaft engines in the near term and probably the mid-term.

WORLDWIDE TECHNOLOGY ASSESSMENT

China, Germany, Japan, and Russia are the world leaders in this category, whereas the United States is the world leader in most facets of mobile electric platform energy systems. Commercial counterparts are unlikely to be developed because of performance, volume, and environmental demands, combined with low production volumes. Most foreign endeavors to develop total mobile electric platform energy systems will be regarded as highly competitive military activities and would require monitoring in the absence of a strong outlook for cooperation

Japan has very advanced commercial fuel cells, and Canada has strength in the niche area of fuel cells.

LIST OF TECHNOLOGY DATA SHEETS
III-7.1. ENERGY CONVERSION AND POWER GENERATION

DATA SHEET III-7.1. LITHIUM THERMAL BATTERY (PRIMARY)

Developing Critical Technology Parameter

Lithium thermal batteries are a fairly mature technology, and major advancements are not expected. They are an energetic system, capable of high power densities with ultra-low impedance (Z); can tolerate severe shock, vibration, and acceleration; will provide 1,500–2,000 W/s; and may be assembled in cell stacks for voltages ranging from 2.5–500 V.

Parameter	1999	Projected by 2010	Nature's Limit
Energy density (W hrs/kg)	850	Similar	
Run times	seconds to hours	Similar	
Shelf life (yrs)	over 15	Similar	
Activation time (ms)	~ 1–10	Similar	

Critical Materials

Better cathodes; electrolytes; insulation materials and heat sources; thermal management systems; squib activators; molten salt electrolytes; separators that tolerate high temperatures; and boron nitride fibers and felts.

Unique Test, Production, Inspection Equipment

None identified.

Unique Software

None identified.

Technical Issues

Reduction in external case and insulation materials to reduce size and weight and increase energy and current density (transitioning to automation is a key factor since devices are currently assembled by hand); extending the discharge period for high-rate lithium-iron disulfide thermal reserve batteries; and battery disposal.

Major Commercial Applications

None identified.

Affordability

Cost-to-performance ratio considerable (i.e., expensive).

RATIONALE

The lithium thermal battery, an unusually reliable and dependable power source, provides energy for seeker head spin-up, infrared (IR) target acquisition with audio confirmation, stabilization of the lead sulfide sensor and internal guidance control system before launch ignition. The thermal battery survives rough handling during transport and adverse environmental combat conditions in the field. Perhaps most impressive are the low demands of technical competence required from users of thermal batteries. This battery is for single-shot use and is activated pyrotechnically. Lithium thermal batteries are essentially unique to military applications and are directly applicable to beyond-visual-range missiles and munitions.

The Air Force Research Laboratory (Propulsion Directorate)/Battery Branch (AFRL/PRPB) Technology Roadmap: Military applications consist of thermal reserve cells used in ballistic missiles and aerospace systems, aircraft ejection seats, fuses, torpedoes, guided artillery, countermeasure devices, intercontinental ballistic missiles (ICBMs), pulsed high-energy weapons, munitions, aircraft emergency power supplies, and inexpensive nuclear triggers. No special access is required.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●●	Germany	●●
India	●	Israel	●	Japan	●●
Russia	●●●	UK	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●●● Moderate R&D ●● Limited R&D ●

The United States is the world leader in this technology: AFRL/PRPB, Wright-Patterson Air Force Base (AFB), Ohio; Eagle-Picher Technologies; LLC, Joplin, Missouri; Argonne National Laboratory; and Invitec, Inc. In addition, the United States pushed this technology for the Poseidon missile system.

Several other countries have known production capability. In particular, Germany (Silverkraft), Israel (Tadiran), and Russia. India may be using these batteries in their ICBMs. Russia's thermal battery remains the power source for the SA-7 Strella, a shoulder-fired ground-to-air anti-aircraft missile. Although the SA-7 is early 1970s technology, it remains in multi-national service, with improvements.

DATA SHEET III-7.1. PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
State-of-the-art PEMFCs can operate for thousands of hours with little loss of performance and can deliver about 700 mW/cm^2 at 80 °C, operating on pure hydrogen at 3 atmospheres pressure and oxygen or air at 5 atmospheres pressure. Catalyst loadings have been reduced to about 0.3 mg platinum/cm^2 for the cathode and less than 0.1 mg platinum/cm^2 for the anode. At ambient atmospheric pressure, performance is reduced to 350 mW/cm^2 of electrode area (NRC, 1997).

PEMFCs consist of a polymer film that permits the passage of protons while blocking electrons and gas.

<table>
<tr><th colspan="4">Pulsed</th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Specific power (kW/kg)</td><td>1</td><td>2</td><td></td></tr>
<tr><td>Specific power (kW/L)</td><td>1</td><td></td><td></td></tr>
<tr><td>Operating temperature (°C)</td><td>40–80</td><td></td><td></td></tr>
<tr><td>Efficiency (%)</td><td>40–50</td><td></td><td></td></tr>
</table>
<table>
<tr><th colspan="4">Continuous</th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Specific power (lb/kW)</td><td>6</td><td>0.1</td><td></td></tr>
<tr><td>Operating temperature (°C)</td><td>40–80</td><td></td><td></td></tr>
<tr><td>Efficiency (%)</td><td>40–50</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>High-conductivity electrolytes; materials for seals or seal technology; light fuel/oxidant storage; and high-performance electrodes.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Technical Issues</td><td>Hydrogen storage; electrolyte membrane durability; higher power densities needed for military applications; and impurities (the platinum electrocatalyst is highly sensitive to impurities in the hydrogen fuel, such as carbon monoxide and sulfur compounds).

Providing hydrogen fuel is one of the major challenges for this technology. Two approaches to surmounting this challenge are hydrogen storage or fuel reformation. Reforming fuel is the focus because of difficulties in storing hydrogen on the battlefield. Such problems include cryogenic, pressurized containment (may or may not be directly exposed to munitions), and the lack of a hydrogen infrastructure to provide remote fueling.</td></tr>
<tr><td>Major Commercial Applications</td><td>EVs; on-site power, portable power, power substations or distributed power, and residential cogeneration.</td></tr>
<tr><td>Affordability</td><td>Because of their inherently slow reaction rate, PEMFCs require an expensive platinum catalyst to speed the process. They currently cost approximately $800 to $1,000/kW, with $50 to $100/kW forecasted by 2005.</td></tr>
</table>

RATIONALE

The PEMFC is also known as a solid polymer electrolyte fuel cell (SPEFC), the proton exchange or polymer electrolyte fuel cell (PEFC), and the ion exchange membrane fuel cell (IEMFC).

PEMFCs could provide space-based weapons an electrical power source with minimal vibration and torque and unmanned aerial vehicles (UAVs) an extended mission life and minimal signatures.

The Air Force Research Laboratory Propulsion Directorate/Power Division (AFRL/PRP) plan for space power: electrical power source for weapons and propulsion power for all-electric UAVs.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●●	Denmark	●●	Finland	●●	France	●●
Germany	●●●●	Italy	●●●	Japan	●●●●	Netherlands	●●
Norway	●●	Spain	●●	Sweden	●●	UK	●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Approximately 85 organizations, including 48 in the United States, are developers. Some of these organization include:

- United States: GE (with Plug Power), H Power, and Avista Laboratories (Spokane, Washington).
- Canada: Ballard, a company of approximately 400 workers and a market of $500 million, in Vancouver, is the world leader.
- Denmark: Mainly academic work.
- Germany: Daimler-Benz, Siemens.
- Italy: DeNora.
- Japan: Toyota ($800 million over 5 years), Matsushita Electric Industrial Company, Sanyo.
- Norway: Norsk-Hydro.
- Spain: ICTP-CSIC.
- United Kingdom: Vickers.
- A Scandinavian consortium exists. It will develop fuel cells and market them in Scandinavia.

DATA SHEET III-7.1. SOLID OXIDE FUEL CELL (SOFC)

Developing Critical Technology Parameter	For SOFCs, pulsed wave applications are mainly applied to weapons, while continuous applications are applied to utilities.

Pulsed			
Parameter	**1999**	**Projected by 2010**	**Nature's Limit**
Specific power (lb/kW)		0.05	
Power Density (W/kg)	> 1,000		
Power density (W/L)	> 1,000		
Operating temperature (°C)	650–1,000		

Continuous			
Parameter	**1999**	**Projected by 2010**	**Nature's Limit**
Specific power (lb/kW)	2	0.1	
Operating temperature (°C)	> 1,000		
Efficiency (%)	40–50		

Critical Materials	High conductivity electrolytes; materials for seals or seal technology; light fuel/oxidant storage; and high-performance electrodes.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Intercell sealing; long-life at high operating temperatures; start-up times; thermal cycling; and higher power densities needed for military applications.
Major Commercial Applications	EVs, on-site power, residential power, cogeneration, and thermal power plants.
Affordability	About $1,000/kW by 2005.

RATIONALE

SOFCs could provide space-based weapons an electrical power source with minimal vibration and torque and UAVs an extended mission life and minimal signatures.

Technology is contained in the AFRL/PRP plan for space power: electrical power source for weapons and propulsion power for all-electric UAVs.

Once the technical issues have been overcome, SOFCs should be an excellent power source for HEVs and for mobile and portable power from logistic fuels. The high operating temperature of the SOFC enables tight thermal integration with the reformer required for logistic fuels. The SOFC can tolerate the impurities from imperfect reformation.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Germany	●●●	Japan	●●
Netherlands	●●●	Sweden	●●	UK	●●
United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Approximately 40 companies worldwide are pursuing this technology. The largest was created with the Siemens purchase of Westinghouse Power Generation in 1998. SOFC development includes:

- United States: EPRI, Ztek Corporation, SOFCo, McDermott
- Germany: Siemens
- Netherlands: Very good in ceramics and thermal engineering.
- Sweden: Academic work.

DATA SHEET III-7.1. MICROTURBINES

Developing Critical Technology Parameter	Microbearings spinning speeds: 1.2 million rpm Compressor efficiency: 65 percent (theoretical) May consume less than 10 gal/hr of hydrogen fuel 50 W of power with a volume < 1 cm^3 **Natures Limits** Power per unit airflow is set by: • Combustor exit temperature (material properties such as creep, oxidation) • Component efficiencies (fabrication constraints, viscous effects, and design technology) • Cycle selection (simple vs. recuperated, cooled vs. uncooled) • Overall pressure ratio (compressor wheel speed, and heat flow into the compressor). Airflow limits are set by: • Rotor blade height constrained by root stress (300–900 m) • Engine diameter (rotor dynamics, manufacturing) • Flow separations from “angular” geometries at low Reynolds Number (flow blockings can be > 50 percent).
Critical Materials	Liquid fuels; hydrogen; and silicon and SiC structures.
Unique Test, Production, Inspection Equipment	Deep reactive ion etching.
Unique Software	Small-scale flow and heat transfer code.
Technical Issues	The following fundamental technology challenges exist: • Creep of Si at high temperature; technology for refractory material microfabrication; high-temperature electrical properties; decoupling of electrical and fluid performance; diffusion at low Reynolds numbers; and improving turbomachinery performance, compressor efficiency losses (approximately 53 percent of loss sources), and catalytic combustion. • Scaling issues include viscous forces (increases at microscale); surface-area-to-volume (increases at microscale); chemical reaction times (invariant); electric field strength (increases at microscale); and manufacturing constraints.
Major Commercial Applications	Power for sensors and portable communication systems.
Affordability	Costs of Si manufacturing of complex systems.

RATIONALE

Microturbines provide high energy and power density and thrust for micro-air vehicles (MAVs), sensors, and portable communication systems at reduced volume and weight. The three enabling technologies for the miniature heat engine are combustors, rotating machinery, and high-temperature material fabrication.

Figure 7-1.1 provides a metric comparison of microturbines and lithium batteries.

	μ Turbogen*	BA-5590 ($LiSO_2$) Battery
Power Output	50 W	50 W
Energy Content	175 W hr	175 W hr
Weight	50 g	1100 g
Volume	50 cc	880 cc
Specific Energy	3500 W hr/kg	175 W hr/kg
Energy Density	3 W hr/cc	0.2 W hr/cc

* Effort lead by MIT; all values include fuel

Figure 7.1-1. Metric Comparison of Microturbines and Lithium Batteries (Source: DARPA)

WORLDWIDE TECHNOLOGY ASSESSMENT

United States ●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

DATA SHEET III-7.1. PHOTOVOLTAICS (PVs)

Developing Critical Technology Parameter

Information concerning generation technologies that produce air mass 0 (AM0)-specific power densities > 400 W/kg is likely controlled. In addition, efficiencies are rated at about 18 percent for the space station, with up to 40-percent achievable (efficiencies are load specific) and a theoretical limit of approximately 50 percent.

For radiation-hardened, space-qualified PV arrays: specific power > 160 W/m^2 under 1 kW/m^2 tungsten at 2,800 K illumination at an operating temperature of +28 °C.

Cell Technology	Commercial Availability	Cost	Power Density (W/m^2)	Efficiency (%)	
				AM0 (space spectrum)	AM1.5 (terrestrial)
Amorphous silicon	Yes	?	50–70		5–10
Polycrystalline silicon	Yes	Low	130–140		14–15
Single-crystal silicon	Yes	High	200	18	20
Gallium arsenide	Yes	High	200		17–18
Indium phosphide	No	High	200		17–18
Copper indium diselinide	No	High	130		15–17
Multibandgap	Yes	High	250		25–30
Concentrator array	Limited	High	250		30

Adapted from: NRC, 1997

Critical Materials

Semiconductor material names can be mentioned (i.e., GaAs, GaInP, and so forth), but specific semiconductor growth and solar cell device processing techniques may be classified if government and proprietary if commercial. Parameters such as layer thickness, doping densities, and metal organic chemical vapor depositions (MOCVD) growth gases, growth temperatures, and growth times may be classified if government and proprietary if commercial.

Unique Test, Production, Inspection Equipment

None identified.

Unique Software

None identified.

Technical Issues

All specific MOCVD semiconductor processing conditions for solar cells with AM0 conversion efficiencies in excess of 20 percent can be classified (if government) or proprietary (if commercial). Expect more graceful aging of component materials 15 to 20 years out. Output of PVs vary seasonally and diurnally.

Major Commercial Applications

High-power communication satellites, remote operations, village power, and recharging batteries.

Affordability

Conventional space Si cells can be ~ \$100/W; high-efficiency Si cells are ~ \$175/W; and the multijunction cells range from ~ \$300–500/W.

RATIONALE

PVs convert solar radiation into electricity. Advantages include stealth, environmentally friendly, long lifetime, modular, and low maintenance. PVs have application for UAVs (extreme high altitude) for power (propulsion).

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	China	●●	France	●●●
Germany	●●●●	India	●●	Japan	●●●
UK	●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

China, Germany, Japan, and the United Kingdom are expected to make attempts to control the future market of solar cells for space applications. China is attempting the capability; however, they are attempting to control the space market by feeding into the competition between GaAs and Silicon. Germany and China are developing GaAs cells for space applications. Sharp (Japan) is the current world leader in silicon-based solar cells for space applications and is looking to control the GaAs market. In Germany, Daimler-Benz Aerospace and the Fraunhofer Institute for Solar Energy Systems are beginning development with GaAs and Siemens is active in PV development. In the United Kingdom, BP Solar is developing thin, lightweight PVs. In the United States, United Solar Systems, Inc., Spectrolab, and Tecstar are active in PV development.

DATA SHEET III-7.1. THERMIONIC CONVERTERS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>Lightweight (< 1kg/m²), deployable, high-performance solar concentrators.
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Converter efficiency (%)</td><td>> 18</td><td>~ 30</td><td></td></tr>
</table></td></tr>
<tr><td>Critical Materials</td><td>High-temperature metals and ceramics; super alloys for vacuum envelops; mono- and polycrystalline refractory alloys for emitter and collector electrodes; oxidation-resistant vacuum envelop materials for terrestrial applications; and lightweight, high reflectivity materials for solar concentrators (e.g., inflatable space structures).</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Refractory alloy fabrication; metal-to-ceramic joining techniques for high-temperature applications; and single crystal refractory alloy manufacturing.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Technical Issues</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>High power for space satellites.</td></tr>
<tr><td>Affordability</td><td>Specialty materials (refractories, ceramics) contributes to present high cost.</td></tr>
</table>

RATIONALE

Thermionic converters are simple, robust, radiation-hard energy conversion devices, which can make them competitive with other forms of energy conversion. The mass of a solar-thermionic power system at power levels above 50 kW can be lower than an equivalent PV-based power system. Preliminary studies indicate the mass of a 50 kW system can be reduced by about one-third. However, this result is strongly dependent on the mass and performance of the solar concentrator used in the thermionic system. For space power applications, solar concentrators must also be considered as a critical technology.

WORLDWIDE TECHNOLOGY ASSESSMENT

Netherlands	●●	Russia	●●●●	Sweden	●●
UK	●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

DATA SHEET III-7.1. EXPLOSIVE MAGNETOHYDRODYNAMIC GENERATORS (EMHDGs)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>The following table assumes power conditioning for many pulses per second (pps).
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Efficiency (%)</td><td>5–12</td><td>> 12</td><td></td></tr>
<tr><td>Energy (depends on frequency: pulses per second)</td><td></td><td></td><td></td></tr>
<tr><td>1 pps</td><td>10 MJ</td><td>100 MJ</td><td></td></tr>
<tr><td>1–100 pps</td><td>100–500 kJ</td><td>1–10 MJ</td><td></td></tr>
<tr><td>100–1000 pps</td><td>1 kJ</td><td>> 1 kJ</td><td></td></tr>
<tr><td>Voltage, radial design (kV)</td><td>~ 20</td><td>> 20</td><td></td></tr>
</table>
(Source: ATAR)</td></tr>
<tr><td>Critical Materials</td><td>None identified.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>1D (Lagrangian), 2D (Eulerian), 3D (not yet available) magnetohydrodynamic (MHD) codes and other modeling software, such as circuit modeling for system integration and explosive modeling software (JWL EOS).</td></tr>
<tr><td>Technical Issues</td><td>Understanding use of, reducing effects of, or eliminating Rayleigh-Taylor instability; design techniques/know-how; high temperature materials; explosive technology (packaging, shapes and sizes); and magnetic and superconducting cable technology.
Because of pollution concerns, use for more than burst modes of operation may not be practical.</td></tr>
<tr><td>Major Commercial Applications</td><td>The commercial market for explosive magnetohydrodynamic (EMHD) technology is likely to be small because of the nature of the conversion process. The primary applications for MHD technologies are pulse generation, electric guns, radio frequency (RF) weapons, and so forth. Because this technology is in the early stage of development, predicting the size of the future market is difficult. The high-pulse energy generation aspect of the technology will probably never appeal to a wide market. EMHD technology, however, has definite potential for several high-energy military consumer applications.</td></tr>
<tr><td>Affordability</td><td>None identified.</td></tr>
</table>

RATIONALE

MHD is an energy conversion technique. It converts the chemical energy of a gas, liquid, or solid fossil fuel directly into useable electricity. For an EMHDG, the potential energy contained in a small amount of explosive is quite large, typically ranging from 4,500 to 6,000 J/g for common explosives. Because the available energy is large and because a solid explosive produces very high gas temperatures and, hence, high electrical conductivity, even MHDGs with relatively low conversion efficiencies are attractive for providing high-energy pulses. Pulses with energy levels in the range from hundreds of kilojoules to hundreds of megajoules and with repetition rates ranging from single shot (at very high energies) to about 1,000 pps (at lower energies) are possible. The major technical problem has been increasing efficiency. Military applications for such a high-energy pulse energy supply are quite diverse, and successful development of a viable system could significantly impact programs ranging from electromagnetic guns to EW systems.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●●	Germany	●●
Japan	●●●●	Russia	●●●●
UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

A few countries (China, Germany, Japan, Russia, and the United Kingdom) have done work on EMHDGs. Russia, however, has made a breakthrough in the development of repetitively pulsed EMHDGs, and it appears to be the only country with capabilities that would benefit the United States. The following foreign organizations have capabilities in MHD generator technology: Russia—the Institute of High Temperature (Moscow) and the High Energy Density Research Laboratory; China—the Southwest Institute of Fluid Physics and the Electrical Engineering Institute (Beijing); Japan—the Tokyo Institute of Technology, the National Chemical Laboratory for Industry (Tsukubu), Kobe Steel, Fuji, Nichicon, [also supported by the Ministry of International Trade and Industry (MITI) and the Agency of Industrial Science and technology (AIST)]; Germany—the Messerschmidt Boikow Blohm (MBB); and the United Kingdom—the Royal Military College of Science (Shrivenham, Swindon) and the Royal Armament R&D Establishment (Chertsey, Surrey).

U.S. firms that have been involved in various aspects of MHD include Babcock and Wilcox, Montana Power Company, TRW, Textron, Westinghouse Electric, STD, ARTEC, and Hercules.

The Russians have thoroughly studied the many complex design and plasma interaction variables that affect linear, disk, and radial EMHDG performance. They have built and operated several experimental generators and confirmed newly formulated, heretofore unreported, interaction phenomena and design concepts. Special repetitively pulsed radial flow cylindrical designs, which take advantage of shockwave phenomena and reduced effects of the Rayleigh-Taylor instability, offer the most promise. The Russians allude to the operation of a large radial generator repetitively using 10 kg explosive charges. This would probably equate to almost 10 MJ/pulse, probably at 20 kV and 1 pps, which is an extraordinary 20-percent efficiency equivalent.

DATA SHEET III-7.1. MAGNETIC FLUX COMPRESSION GENERATORS (MFCGs)

Developing Critical Technology Parameter

Parameter	1999	Projected by 2010	Nature's Limit
Discharge time (μs)	few to 500		
Energy (eV/Å^3)	several	20	
Current pulse (MA)	> 250		
Efficiency (%)	< 10		

Discharge Time: varies from a few microseconds to 500 μs currently. This can be longer but probably begins to be impractical.

Energy: 20 eV/Å^3 (3 MJ/cm^3) projected by 2010. This projected energy density is based on the Russian claim of a 28-MG field.

Current Pulse: The limit is mainly an economic one. The output conductor should carry probably not much more than 700–800 kA/cm in the time scales for useful power sources. Thus, 1 GA needs a 10- to 15-m wide output conductor. Practically, one would parallel several smaller devices.

Efficiency: Efficiencies are very much generator type and load dependent, seldom exceeding a few percent for practical loads.

Critical Materials	Highly conductive materials, such as copper and aluminum. In addition, these materials should also have good elastic properties.
Unique Test, Production, Inspection Equipment	Helical flux compression generators (HFCGs) have low impedance and thus require conditioning to match that of the load. This conditioning must also provide temporal matching since loads may require very fast rise times (hundreds of nanoseconds).
Unique Software	MACH3: Three dimensional (3-D) MHD code under development.
Technical Issues	Blow-by in propellant-driven systems.
Major Commercial Applications	None, because of single-shot nature.
Affordability	None identified.

RATIONALE

An MFCG uses explosive energy to compress a magnetic field, thereby creating an intense energy pulse. This technology is generally single shot since the explosion destroys parts of the device. An MFCG functions by building up a magnetic field in coils and setting off an explosion (destroying many of the windings). With the reluctance of the circuit altered, the magnetic flux is compressed, increasing the strength of the field and producing an intense current. “When the desired output is an intense magnetic field itself, the technique is generally referred to as MFC, and when the desired output is an intense current pulse for some electrical load, it is generally referred to as a magnetocumulative generator (MCG) (ATAR, 1994).

As a side note, MCGs are mainly a Russian designation.

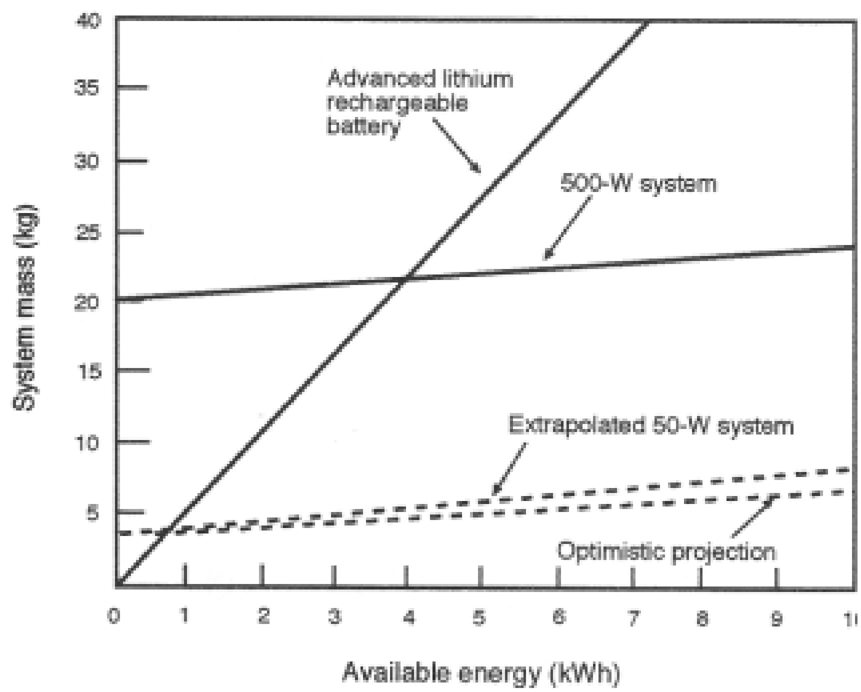
WORLDWIDE TECHNOLOGY ASSESSMENT

China		Japan		Russia		United States	
●●		●●		●●●●		●●●	

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

MFCG research is taking place in Russia at the All-Russia Scientific Research Institute of Experimental Physics (VNIIEF) and at TRINITI. Most of the MFCG research in the United States takes place at Los Alamos National Laboratory (LANL).

DATA SHEET III-7.1. ALKALI METAL THERMAL TO ELECTRIC CONVERTER

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Cell efficiency (%)</td><td>25</td><td>30</td><td>50</td></tr>
<tr><td>System efficiency (%)</td><td>15</td><td>20</td><td>30</td></tr>
<tr><td>Total power (kW_e)</td><td>> 50</td><td>100</td><td>100</td></tr>
</table>


Source: NRC, 1995
</td></tr>
<tr><td>Critical Materials</td><td>Beta alumina solid electrolyte, seals, membranes, bearings, and insulators.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Thermo-vac chambers.</td></tr>
<tr><td>Unique Software</td><td>Any thermodynamic-electrochemistry-coupled code.</td></tr>
<tr><td>Technical Issues</td><td>Joining technologies (ceramic/ceramic, ceramic/metal, metal/metal) capable of surviving sodium vapor environment (900 °C) for 10 years; materials that maintain strength, thermal conductivity, and emissivity (properties) at high temperature (900 °C); high-performance electrode/collector/beta alumina solid electrolyte (BASE) systems and wick structures; and gas-to-converter source of efficiency loss.</td></tr>
<tr><td>Major Commercial Applications</td><td>Bottoming cycles for power-generation plants; cogeneration systems; stand-alone and remote power supplies; and space applications.</td></tr>
<tr><td>Affordability</td><td>This technology has the potential to become affordable ($10/W_e$) and must become so to compete with existing technologies terrestrially.</td></tr>
</table>

RATIONALE

An AMTEC device can convert heat from any source to electric power. A solar thermal power conversion system based on an AMTEC has advantages over other technologies (including PV systems) in terms of the total power that can be achieved with such a system and the simplicity of the system [which includes the collector, energy storage (thermal storage with phase change material) and power conversion in a compact unit]. The overall system could achieve as high as 14 W_e/kg with present collector technology and future AMTEC conversion efficiencies. The energy storage system outperforms batteries, and the temperatures at which the system operates allows long life and reduced radiator size (heat reject temperature of 600 K).

The AMTEC technology is based on a unique material (BASE) that allows the energy conversion to take place. This material is well known, but supplies are limited because of the present small market. BASE is not difficult to make—nor are any other components that make up an AMTEC cell. Thus, the hope is that the result will be affordable. The technology is being developed by several agencies interested in its use, including the United States Air Force (USAF) the Jet Propulsion Laboratory (JPL), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE). The USAF is solely pushing the technology toward a high-performance goal. The major technical issues that need to be addressed are use of the proper high-temperature materials that exhibit the most ideal properties, joining technologies, and component technologies, such as the collector/electrode system, wicks, condensers, and so forth, that can withstand operation in a high-temperature sodium environment for approximately 10 years.

This technology is capable of achieving greater than 50 kW_e on a space platform and, therefore, is enabling for several technologies and missions in space.

WORLDWIDE TECHNOLOGY ASSESSMENT

Japan	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

In the United States, the following organizations are developing this technology: Westinghouse; Advanced Modular Power Systems, Inc.; Dynamic Structures and Materials; LCC; Thermacore; and Trition. India is using AMTEC for terrestrial purposes.

SECTION 7.2—ENERGY STORAGE

Highlights

- Energy is stored either chemically, mechanically, or electrically, with durations of microseconds to years.
- Fast-storage devices are militarily critical for weaponry.

OVERVIEW

Energy storage devices are intended for pulsed applications requiring short-term storage (microsecond-to-second) through long-term storage (several years). These devices can be charged and discharged in a pulsed or near-continuous manner. Examples of technologies used as energy storage include batteries, capacitors, inductors, and flywheels or rotating machinery.

Energy can be stored chemically, mechanically, or electrically. For mechanical storage, the energy is stored in the rotary motion of machinery, such as a flywheel. For electrical storage, the energy is stored in the electric field of the dielectric medium, such as a capacitor, or in the magnetic field of the dielectric medium, such as an inductor. For chemical storage, the energy is stored in the reactants (as in batteries).

For pulsed-power applications, once energy is stored, it can then be extracted completely or in small portions. In the mechanical case, the flywheel storage device can be coupled to a switch or a switching network that, depending on the speed and other characteristics, can deliver pulses of power to some load. Some devices integrate the switching into the storage device and feed its pulsed output directly to the load. Once charging is complete, the switch is closed and a pulse is delivered to the load. High-frequency inverters (DC-to-AC) can be used as a power supply to charge the storage device in a few milliseconds. Once charging is complete, a switch is closed, and pulsed power is delivered to some load.

In the high-energy case, mainly for weapons applications, systems of average powers in excess of 100 MW, for times of seconds to minutes, are integrated with pulsed-energy conditioning to create gigawatt-class repetitive pulses of energy from milliseconds down through submicroseconds, at voltages from several kilovolts up to megavolts. There may emerge selected military applications, such as high-power radars, electronic countermeasures, and directed energy weapons (DEWs), that demand a class of precisely conditioned electric energy that has no direct foreseeable commercial or industrial application. However, industry may be able to use for different applications the components used to produce these levels of output. High-energy electronics have no current commercial applications. Assured development, therefore, will require government sponsorship.

Peak power, pulse shape, pulse duration, repetition rates, firing rates, silent watch, and system energy storage recharging times represent militarily critical performance parameters that, in many cases, transcend known commercial, industrial, or consumer applications. In addition, high-energy electronics packaging currently requires parallel/series combinations of components in the power train to achieve reliability, fault tolerance, and graceful aging at performance levels greater than 10 times today's commercial standards.

RATIONALE

Fast-storage devices are militarily critical for weapons. However, energy is generally collected or available from the prime source at low-power levels and power densities. To meet common load requirements, such as high power, the energy is released from storage over an extremely short duration and converted into a pulsed-power form.

Electric power systems are critical enabling technology subsystems in all nuclear devices and nuclear weapons effects simulators. Some of these applications require single-shot devices. Many of the specific technologies involved are dual use.

WORLDWIDE TECHNOLOGY ASSESSMENT

The United States is a world leader in many areas of battery technology, but Japan is ahead in specific areas. In addition, the Europeans have a strong capability in small-lot production of high-reliability batteries that could be of great benefit to the United States. The U.S. Advanced Battery Consortium (ABC,) consisting of the Electric Power Research Institute (EPRI), Argonne National Laboratory, Sandia National Laboratories, and the Nonlinear electronics Laboratory (NOEL) are major government players working with the big three auto makers [Chrysler, Ford, and General Motors(GM)] to develop batteries for EVs. In addition, the following private firms have ongoing R&D in advanced batteries:

- Eagle Picher (nickel-metal hydride, lithium thermal)
- Yardney (lithium ion)
- Electro Energy (nickel-metal hydride)
- Valence Technology (lithium polymer)
- SAFT America (lithium ion)
- Ovonics (nickel-metal hydride)
- Duracell (nickel-metal hydride)
- Eveready (lithium ion)
- Rayovac (lithium ion)
- Wilson Greatbatch (lithium ion).

Lithium battery research elicits particular interest. Table 7.2-1 lists the main North American R&D contributors in industry. Table 7.2-2 lists the North American contributors from laboratories and universities. Table 7.2-3 lists the lithium battery R&D contributors from foreign industry. Table 7.2-4 lists the lithium battery contributors from foreign universities. Table 7.2-5 lists the lithium battery R&D contributors from foreign laboratories.

Table 7.2-1. North American Industry Lithium R&D (Source: NATIBO)

Companies		
Advanced Energy Technologies, Inc.	ECO Energy Conversion	Mine Safety Appliances Company
Advanced Technology and Research, Inc.	EIC Laboratories	Moli Energy
Alliant Techsystems Inc.	Electrochemica Corporation	Panasonic
Applied Power International	Electrofuel	PolyPlus Battery Company
ARCO Medical	Energy Conversion	Power Conversion, Inc.
Arthur D. Little, Inc.	Eveready	Ray-O-Vac
ATT Bell Laboratories	GE Neutron Devices	SAFT - America
Aurora Flight Sciences Corporation	General Dynamics Space Systems	Sony
Ballard	General Motors	Sharp
Battery Engineering, Inc.	Gould, Inc.	SRI International
Bellcore	HED Battery Corporation	Technochem
Bell Labs	HEDB Corporation	The Aerospace Corporation
Catalyst Research	Hoppecke Battery Systems, Inc.	Ultralife Technologies
Coastal Systems Station	Johnson Controls	U.S. Advanced Battery Consortium
Covalent Associates	Lithium Energy Associates	UCAR Caron Company
Dowty Batteries	Martin Marietta Aerospace	Valence Technology
Delco Remy	Maxell Corporation of America	Westinghouse Electric Corporation
Duracell, Inc.	Medtronics, Inc.	Wilson Greatbach Limited
Eagle-Picher Industries	Microchip Technology, Inc.	W.R. Grace

Table 7.2-2. North American Laboratory and University Lithium R&D (Adapted From NATIBO)

Laboratories	Universities
AFRL	California Institute of Technology
ARLs	Harvard University
Argonne National Laboratories	Polytechnic University
Bell Labs	Texas A&M University
Marshall Space Flight Center	University of Dayton Research Institute
Naval Warfare Center	University Kentucky
Hydro Quebec	University of Minnesota
Jet Propulsion Laboratory	University of Pennsylvania
Lawrence Berkeley Laboratory	University of Texas
National Research Council, Canada	University of Texas at Austin
Naval Surface Warfare Center, Crane	University of Waterloo
Naval Surface Warfare Center, White Oak	University of Ottawa
Naval weapons Support Center	
Oak Ridge National Laboratory	
Sandia National Laboratories	
U.S. Air Force Space and Missile Center	
U.S. Army EDTL	
Wright Patterson Air Force Base	

Table 7.2-3. Foreign Industry Lithium R&D (Source: NATIBO)

Country	Company	Chemistry
United Kingdom	AEA	Rechargable lithium batteries
	SAFT NIFE	Lithium ion secondary and lithium thionyl chloride
	Dowty Batteries	Lithium manganese dioxide batteries
	Dorutcy	Lithium manganese dioxide batteries
	British ARE	Lithium iron sulfides
	Oakdale Batteries	Lithium aluminum iron sulfide secondary batteries for submarines
	Vickers	Lithium iron sulfides
	VSEL	Lithium aluminum iron sulfide secondary batteries for submarines
Germany	Varta AG	Lithium polymer secondary and lithium thermal
	BAFF	Lithium polymer secondary and lithium thermal
	Bayer Fulrik	Lithium polymer secondary and lithium thermal
	Hoppecke Betterien	Lithium primary batteries
	Siemens	Lithium primary batteries
Israel	Tadiran	Lithium ion
	Israel Defense Forces Power Sources Division	Lithium ion
Belgium	SEDEMA	Rechargable lithium cells
Switzerland	RENATA	Secondary lithium batteries

Table 7.2-3. Foreign Industry Lithium R&D (Source: NATIBO) (Continued)

Country	Company	Chemistry
Japan	Central Glass Company Ltd.	Lithium ion secondary, lithium polymer, lithium iron sulfide, and lithium ion cells
	Sony	Lithium ion secondary, lithium polymer, lithium iron sulfide, and lithium ion cells
	Toshiba Asahi Chemical Joint Venture	Lithium ion secondary, lithium polymer, lithium iron sulfide, and lithium ion cells
	Hitachi	Lithium ion secondary, lithium polymer, lithium iron sulfide, and lithium ion cells
	Sanyo	Lithium ion secondary, lithium polymer, lithium iron sulfide, and lithium ion cells
	Asahi	Lithium ion secondary, lithium polymer, lithium iron sulfide, and lithium ion cells
	Yuasa	Lithium ion secondary, lithium polymer, lithium iron sulfide, and lithium ion cells
	Matsushita	Lithium ion secondary, lithium polymer, lithium iron sulfide, and lithium ion cells
	Mitsubishi Petrochemical Company	Lithium ion secondary, lithium polymer, lithium iron sulfide, and lithium ion cells
	Sharp	Lithium ion secondary, lithium polymer, lithium iron sulfide, and lithium ion cells
	Honda Research and Development Corporation	Lithium ion technology
France	SAFT	Lithium ion secondary, lithium polymer, lithium thionyl chloride, lithium thermal, and lithium vanadium pentoxide
	Alcatel	Rechargable lithium cells
	INSA	Rechargable lithium cells

Table 7.2-4. Foreign Universities Lithium R&D (Source: NATIBO)

Country	University
Bulgaria	Bulgarian Academy of Sciences
China	Bejing Institute of Spacecraft System Engineering
	Changchun Institute of Applied Chemistry
	Chinese Academy of Sciences
	Tianjin Institute of Power Sources
	Institute of Physics, Academia Sinica
	Tianjin University, Department of Applied Chemistry
Czech Republic	Wuhan University
Denmark	Technical University of Denmark
France	CNRS - FranceCzech Academy of Sciences
	SORAPEC
	Universite Bordeaux
Germany	Dresden University of Technology, Institute of Physical Chemistry and Electrochemistry
	Ernst-Moritz-Arndt University of Greifswald
	Fraunhofer-Institute for Chemical Technology
	Merseburg University, Institute of Macromolecular Chemistry
	University of Munster

Table 7.2-4. Foreign Universities Lithium R&D (Source: NATIBO) (Continued)

Country	University
Greece	Aristotelian University University of Ulm
Israel	Bar-Ilan University Tel Aviv University
Italy	Universita di Bologna
Japan	Chuba University Iwate University Keio University Kyoto University Mie University Rikkyo University NTT Interdisciplinary Research Laboratories Shinshu University Tokyo Institute of Technology Yamaguchi University
Netherlands	Delft University of Technology
Poland	Central Laboratory of Batteries and Cells Technical University of Poznan, Institute of Chemistry and Applied Electrochemistry University of Warsaw
Russia	A.N. Frumkin Institute of Electrochemistry of the Russian Academy of Sciences Frumkin Institute of Electrochemistry Institute of Chemical Engineering Institute of Transportation Engineering Russian Academy of Sciences Saratov State University
Scotland	University of St. Andrews
Slovenia	National Institute of Chemistry
Taiwan	National Central University Chung Shan Institute of Science and Technology

Table 7.2-5. Foreign Laboratories Lithium R&D (Source: NATIBO)

Country	Laboratory
Australia	Australian Army Engineering Development Establishment
France	Laboratoire d'Ionique et d'Electrochimie du Solide, Institute National Polytechnique de Grenoble Laboratoire de Chimie du Solide Mineral

LIST OF TECHNOLOGY DATA SHEETS
III-7.2. ENERGY STORAGE

DATA SHEET III-7.2. FLYWHEELS

Developing Critical Technology Parameter	A flywheel is an energy storage system. As such, its performance is defined by the following parameters: • Total energy density (based upon maximum rotational speed) • Useable energy density ("depth of discharge," from maximum/minimum speed ratio) • Power density • Life (i.e., number of cycles to failure) • Output voltage variation (i.e., approaches that minimize this may be militarily critical) • Coefficient of friction (i.e., drag) caused by idling losses in support system. Since flywheels are spinning bodies, an additional parameter that defines acceptable vibration levels (e.g., allowable spectrum at bearing mounts) imparted to the host platform should be considered. Further, a key parameter is tip speed, the product of angular velocity and radius. Research objectives include high-energy density and high-energy rate (power) extraction for a variety of high-energy consumer applications (e.g., DEWs and HEVs).
Critical Materials	High strength-to-weight ratio materials (composites) for energy storage rotor; high-temperature superconducting materials for LOW-drag passive magnetic bearings; techniques for high-energy rate/high peak power extraction; magnetic (and other) bearing technologies for long storage life and efficient operation; and materials such as Kevlar, Metglass, and graphite epoxy.
Unique Test, Production, Inspection Equipment	Flywheels are typically high-energy devices that require a high-vacuum spin pit for operational testing. Fabrication of the flywheel typically requires precisely controlled filament winding machinery (if it is a spun composite wheel). Equipment is in place for balancing rotating electromagnetic equipment (at rotational rates > 2,500 rpm and having a rotating mass > 1,000 kg). However, one aspect of magnetic bearings is that they allow the rotor to spin about its inertial center. The rotor "auto-balances" when operated at typical speeds of interest for flywheels. The balance has to be fairly precise, but other applications are probably more demanding from this standpoint.
Unique Software	Active magnetic bearings are often used for flywheel suspension. The control logic is typically custom designed and implemented on a digital signal processor board. Specialized analysis codes, often proprietary, are used for analysis of flywheel stresses and system dynamics.
Technical Issues	System safety; design approaches offering graceful degradation; predictable rotor dynamics and stability; platform vibration suppression for space applications (closely related); and overall system integration for the battlefield environment (a major technical challenge).
Major Commercial Applications	UPSs, utility-level energy storage, low earth orbit (LEO) satellites, and rock splitting (fracturing).
Affordability	None identified.

RATIONALE

Rotating energy storage is of interest because it potentially offers higher power densities than batteries and higher energy densities than capacitors. Electromechanical storage systems (flywheels) use the mechanical inertia in a rotating mass. Because the energy stored increases with square of the angular velocity and only linearly with mass, current developments stress the use of composite material capable of withstanding the centrifugal forces and angular decelerations associated with extracting high peak powers (10^9 watts) from masses rotating at thousands of RPM. Flywheel systems can be used for continuous or near-continuous duty (e.g., in electric vehicles) as well as for pulsed applications (ATAR, p. II-45).

A flywheel system can be effective at storing and delivering energy. These two functions are independent (i.e., power density and energy density are decoupled). System mass savings are significant in space applications, where the functions of attitude control and energy storage can be combined. Comparing this technology with batteries is logical. If a battery satisfies the requirements of a particular application, the battery is likely a simpler device and should be used. However, for some applications, the flywheel will be the best choice when life-cycle cost is considered (i.e., the necessary derating factors, increasing control and system complexity, and possibly limited life of batteries). Flywheels and batteries should be considered complementary, with each having its own applications.

Flywheels are being used in conjunction with high-temperature superconductivity to produce a nearly frictionless flywheel that will be able to store high levels of energy, with little energy lost in the process. Such flywheels are enclosed in a vacuum to reduce rotational friction loads. Flywheels are being used as advanced energy storage devices in EVs.

Materials such as Kevlar, Metglass, and graphite epoxy and their production processes for flywheel forming are still being tested to determine operating limits and optimum choices. Such materials tend to fail when operated above design speeds. Testing must be extensive to take into account effects of temperature, fatigue, and creep. There are ongoing efforts to address flywheel safety in the United States. One way to ensure safe operation is to derate the system so that it is never stressed to anywhere near the limits of the materials used in the rotating element.

Potential military applications of flywheel technology include HEVs, satellite energy storage, and small- or medium-caliber electric guns. These developments are long term and partially driven by the fact that the development of the technology for electric cars is not expected to move beyond the prototype stage for many years. Recent technology development and integration programs at the Defense Advanced Research Projects Agency (DARPA), especially the Combat Hybrid Power Systems (CHPS), will be the first demonstration of robust military mobile platform energy systems that explicitly maximize energy management at the system level.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	Germany	●●●●	France	●●●
Japan	●●●	Russia	●●●●	Ukraine	●●
UK	●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The major foreign players for flywheel technology include: Canada: Flywheel Energy Storage (Ottawa); France: ONERA, Peugeot; Germany: Magnet-Motor (flywheels are used commercially in a large number of transit buses); Japan: Toyota, Kawasaki, Yanmar, Toshiba, Nippon Steel; Russia: Yfremov Inst. (St. Petersburg), Institute of Atomic Energy (Moscow), Institute for Electrophysical Apparatus, Institute for Electrophysics, Institute of High Temperature; Ukraine: Institute of Electrodynamics (Kiev), Physical-Technical Institute (Kharkov); and the United Kingdom: British Petroleum (BP).

For equipment to balance the rotating electromagnetic equipment, the United States leads in development followed by the United Kingdom, Germany, and Brazil (which would rate equally thereafter).

DATA SHEET III-7.2. LITHIUM ION BATTERY (RECHARGABLE)

Developing Critical Technology Parameter	The rechargeable lithium ion battery—a solid-state type battery system originally developed by Sony of Japan and based on lithium intercalculation chemistry and lithium-ion transport systems—is a relatively new and rapidly developing technology. This battery is a safe and sealed system, does not use metallic lithium, and can be recycled with reclaimed materials. Estimated cost is $400–600/kW. By 2005, projections indicate a very high cell voltage (3.6 to 4.2 V/cell) and production in prismatic and cylindrical configurations. Expected commercial markets include EVs, computers, telecommunications, and portable electronics. This system is very attractive for military use in soldier systems. A 270-V and/or bipolar designs are expected.

Pulsed

Parameter	1999	Projected by 2010	Nature's Limit
Energy density (W hrs/kg)	70–80	150–200	
Power density (W/kg)	360	1,000 (18–20 sec pulse)	
Cycle life (# cycles)	500–1,000	> 4,000	
Temperature range (°C)	–30 to +50	–30 to +50	
Recharge time (hrs)	2–4	2	

Continuous

Parameter	1999	Projected by 2010	Nature's Limit
Energy density (W hrs/kg)	100–150	220	
Power density (W/kg)	250	800–1,200	
Cycle life (# cycles)	> 500	1,200–2,000 (up to 5 yrs.)	
Temperature range (°C)	–20 to +50	–30 to +50	
Recharge time (hrs)	> 10	~ 10	

Graphite Fiber–Lithium Ion Rechargables (Projections)

Several R&D efforts are directed at a rechargable battery based on graphite fiber electrodes and a lithium ionic salt in an organic electrolyte. Preliminary projections give:

Continuous		Pulsed
Parameter	Projection	Projection
Energy density (W hrs/kg)	120	
Power density (W/kg)	360	up to 1,000
Cycle life (# cycles)	1,000s	1,000s
Temperature range (°C)	–20 to +60	–20 to +60

Critical Materials	Carbon materials: powders, platelets, fibers, and nanotubes; new organic electrolytes and electrolytic additives to enhance lithium-ion conductivity and reduce resistivity; lithiated transition metal oxides of cobalt, nickel, and manganese; composite electrodes; spinels of managnese oxides (e.g. MnO_2 and M_2O_4); high-conductivity polymer electrolytes; and high-energy density anodes and cathodes.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Modeling and software codes are advanced and possibly available to the commercial market.

Technical Issues	Cost; improvement of low-temperature performance and safety; development of carbon materials with greater reversible lithium intercalculation capacity; less costly lithiated nickel-metal oxide electrodes and less costly electrolytic salt additives to enhance lithium ion conductivity; high conductivity over a broad temperature range; less sensitive cathodes with a broad charging voltage range; individual cell control during charge; and large capacity cells with 25- to 200-Ah capacity. Critical emphasis for military R&D is the development of low-temperature electrolytes. Carbon particles may pose a safety problem (flash fires). The electrodes are made of fine carbon particles with high density. The shock wave from a munition may incite a pyrophoric reaction. These batteries have only been field tested for transportation—not for *combat.*
Major Commercial Applications	Automobiles, aircraft, and avionics; air/sea rescue systems; navigation aids; marine and boating; EVs; commercial satellites; cell phones; laptop computers; and portable electronic devices. The last three applications are not driving military technology development. Most applications in this area are separate from the more robust military applications.
Affordability	Currently, commercial and military markets are quite disparate in this area; driven primarily by SAFT (France) and U.S. technology.

RATIONALE

Lithium ion batteries could provide 50-percent or greater reduction in battery weight and volume for space and other applications. The eliminate cadmium and lead use in rechargeable batteries and will replace nickel-cadmium rechargables. Lithium ion batteries are an affordable secondary battery with a low self-discharge rate and extend service life. In addition they promote the use on an environmentally friendly and recyclable power source. **Note:** *Lithium ion batteries represent the fastest growing and most profitable sector of the battery market and industry. These batteries are a hot academic topic.*

AFRL/PRPB Technology Roadmap: Aircraft, UAVs, space-based radar (SBR), space-based laser (SBL), and all satellite power supplies. Non-radiation hardened commercial batteries suffer a separator breakdown in a space environment, therefore, commercial batteries cannot be used in space applications.

Development programs for specific military applications are needed. Military applications include portable electronics, soldier support systems, computers, night vision, lasers, telecommunications, EVs, robotics, aerospace, missiles, satellites, aircraft, and avionics. These batteries will strongly compete with nickel-based batteries.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	China	●●	Denmark	●●	Finland	●
France	●●●	Germany	●●●	Italy	●●	Japan	●●●●
Russia	●	South Korea	●●	Taiwan	●●	UK	●●
United States	●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Lithium ion batteries are commercially produced in China, Denmark, France, Germany, Japan, South Korea, Taiwan, and the United Kingdom. Most batteries are small cylindrical or prismatic cells, made by numerous small and large manufacturers.

In the United States, the following organizations are involved in developing this technology: AFRL/PRPB, Wright-Patterson AFB, Ohio; SAFT (America); Yardney; Eveready; Rayovac; and Wilson Greatbatch. PolyStor (Dublin, California) is producing a combination of lithium ion battery (or other rechargables) and an ultracapacitor for a smart power source. For man-portable power supplies, this significantly reduces weight. For example, the capacitor aspect would be used in pulsed applications, with overdrain of the battery charging the capacitor.

Foreign companies working to achieve this goal include the following: In France, SAFT (France) [producing nickel-hydrogen batteries (SAFT America)]; in Germany, Varta Battery, Sonnenschein Lithium GbH, and Accumulatorenwerke Hoppecke (developing secondary lithium ion for space use); and in Japan, Matsushita Battery Industrial Company (Panasonic), Sony Corporation, and Mitsubishi Petrochemical Co., Ltd. Granaria Corporation of the Netherlands is attempting to purchase Eagle-Picher, a U.S. manufacturer and world leader in space batteries, particularly nickel-hydrogen. Eagle-Picher currently has the space battery market.

Several foreign nations are in the lead for developing secondary lithium ion batteries for space use. These countries include France, Germany, Israel, Japan, and the Netherlands. Japan and France are attempting to capture the space battery market (to include foreign satellites), while Israel would like to produce the batteries compatible with their own spacecraft. France, Germany, and Japan have state-of-the-art battery research programs.

The commercial market is rapidly growing, with portable electronics and emerging EVs as the drivers. The cycle life and depth of discharge are the major differences between military and commercial applications. Commercially, Japan is and will continue to be the world leader in this tecnology.

DATA SHEET III- 7.2. LITHIUM POLYMER BATTERY (RECHARGABLE)

Developing Critical Technology Parameter	The rechargable lithium polymer battery is a new and emerging technology (more recent than lithium ion batteries). It is a solid-state battery based on Ion conductivity in polymers. The system is lightweight and safe and uses non-toxic materials. The rawbacks are poor low temperature and high rate performance. Pulsed applications include weapons and acceleration for HEVs, while CW applications may focus on EVs. By 2005, the following are projected for rechargable lithium polymer batteries: use of a solid conductive polymer membrane electrolyte or gel electrolyte; very compact size and cell design; more flexibility; and able to have battery molded in various shapes and configurations. Key problems are poor low temperature performance (below 0 °C) and low charge/discharge rates. Battery uses lightweight materials. Projected costs are ~ $200 to 300/kW.

Pulsed

Parameter	1999	Projected by 2010	Nature's Limit
Energy density (W hrs/kg)	125	300–400	
Power density (W/kg)	200	400	
Cycle life (# cycles)	200–300	2,000	
Temperature range (°C)	–20 to +100	–40 to +150	
Recharge time (min)	> 15	~ 15	

Continuous

Parameter	1999	Projected by 2010	Nature's Limit
Energy density (W hrs/kg)	< 125	300–400	
Power density (W/kg)	100	400	
Cycle life (# cycles)	300	500–1,000	
Temperature range (°C)	–20 to +100	–40 to +150	
Recharge time (min)	> 15	~ 15	

Critical Materials	High conductivity polymer electrolytes and gels; high-energy density anodes and cathodes; gelionic materials; conductive elastomers (rubbers); complex organo-lithium salts; carbon powders; carbon platelets and fibers; and new polymers with high breakdown voltages.
Unique Test, Production, Inspection Equipment	Assembly or production must take place in a dry atmosphere because of lithium's reactive nature with moisture. In addition, the battery must be hermetically sealed.
Unique Software	None identified.
Technical Issues	High conductivity over a broad temperature range; less-sensitive cathodes with a broad charging voltage range; cost reduction; making high-rate batteries; and large capacity cells with 10- to 100-Ah capacity.
Major Commercial Applications	Commercial satellites; cell phones; laptop computers; and portable electronic devices. Primary drive is form flexibility, high cell-packing density, and reduced weight. The last three applications are not driving military technology development.
Affordability	None identified.

RATIONALE

Rechargable lithium polymer batteries offer a 50-percent or greater reduction in battery weight for space applications, flexible battery configurations, amd greatly improved packing density and spce/volume use. Batteries can tolerate additional flexing, distortion, bending, shock, perforation, and vibration. The battery is perhaps the most attractive power source emerging for soldier support systems becaues of its form flexibility. Military applications include lightweight, compact power supplies for soldier support systems.

AFRL/PRPB Technology Roadmap: SBR, SBL, and all satellite power supplies.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●●	France	●●
Germany	●●	Italy	●●
Japan	●●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Asian countries, particularly Japan, are key technology developers for commercial applications.

In the United States, the following organization is active in developing this technology: AFRL/PRPB, Wright-Patterson AFB, Ohio.

In Japan, the following organization is active in developing this technology: Sony Corporation.

The world leader is a joint U.S.–Canadian venture that includes 3M, Argonne National Laboratory, and Hydro-Quebec.

DATA SHEET III-7.2. NICKEL METAL HYDRIDE BATTERY (RECHARGABLE)

Developing Critical Technology Parameter

The rechargable nickel metal hydride battery is a commercial technology developed to find an environmental replacement for NiCd batteries, particularly in portable electronic devices and EVs. These batteries are environmentally safer and offer longer operating times and higher energy output but cost approximately 25 percent more than similar-size NiCd batteries.

Pulsed			
Parameter	**1999**	**Projected by 2010**	**Nature's Limit**
Energy density (kW/kg)	> 1		
Recharge time (min)	5–10	~ 5	

Continuous			
Parameter	**1999**	**Projected by 2010**	**Nature's Limit**
Energy density (W hrs/kg)	65–90	160	
Power density (W/kg)	160	500	
Cycle life (# cycles)	600–1,000	1,500–3,000	
Temperature range (°C)	–10 to +30	–25 to +50	
Recharge time (min)	60–180	30	

Critical Materials	Metal hydride materials.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Longer cycle life; degradation mechanism; tighter charge control algorits; compatibility with existing aircraft power systems. Operation over the temperature range from –40 to +70 °C. Large commercial automotive batteries limited to –10 to +40 °C operation.
Major Commercial Applications	Automobiles; commercial aircraft;power tools; and personal electronic devices.
Affordability	Prices currently driven by the personal electronic device applications. EV batteries are expensive because of limited production ($300–400/kWh). Projected costs for an aircraft battery are estimated at $500/A hr.

RATIONALE

Rechargable nickel metal hydride batteries eliminate cadmium and lead use in rechargeable batteries. For aircraft applications, they reduce size and weight by 35 to 50 percent.

AFRL/PRPB Technology Roadmap: aircraft, UAVs, and satellite power. Cost reduction for military applications.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	China	●●	France	●●●
Germany	●●●	Israel	●●	Japan	●●●
Russia	●●	South Korea	●●	Taiwan	●●
Ukraine	●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States appears to be the only country developing this technology for aircraft applications. Foreign companies are concentrating on commercial terrestrial applications.

Most of the commercial development is in Asia. In Japan, the following organizations are active in developing this technology: Matsushita, Sanyo, Toshiba, and Yuasa Battery Company.

The following are the North American NiMH R&D organizations:

- **Industry.** COMSAT Corporation; Duracell; Eagle-Picher Industries; Electro-Energy, Inc.; Eveready Battery Company; Lockheed Engineering and Sciences Company; Maxell; Ovionic Battery Corporation; Rockwell International; and the Aerospace Corporation
- **Laboratories.** Argonne National Laboratory; Idaho National Laboratory; NASA Johnson Space Center; NASA Lewis Research Center; and AFRL/PRPB, Wright Patterson AFB, Ohio
- **Universities.** Rutgers University, Texas A&M University; Texas Research Institute; and University of Alabama at Huntsville.

In the United States, only Ovonics Battery Corporation in Troy, Michigan, is developing the transition metal AB2 metal hydride alloys for EVs. Ovonics appears to have a lock on patents for manufacturing of the AB2 metal hydride alloys. Electro Energy, Inc., Danbury, Connecticut, a small business, is developing a bipolar design using the AB5 metal hydrides. No other company worldwide is known to be pursuing a bipolar design metal hydride battery.

In Europe, the following organizations are active in developing this technology: In Germany, Varta AG, BAFF, Bayer Fulrik, Siemens, and, in France, Aerospatiale, Alcatel, and SAFT. In France, SAFT is developing the lanthanide series AB5 alloys for EV applications and other applications as are the various Japanese and Korean companies. The United Kingdom gets some of these batteries from Japan.

DATA SHEET III-7.2. SILVER ZINC BATTERY (RECHARGABLE)

Developing Critical Technology Parameter	The rechargable silver zinc battery is a mature well-established technology with a limited, mostly military/aerospace market because of high cost. Because of the maturity of this technology, little progress or advancement is expected by 2005. Secondary silver zinc alkaline batteries are very energetic, have a cell voltage of about 1.8 V/cell, wide operational temperature range (–40 to +50 °C), and relatively high energy density (100–250 W hrs/kg) depending on battery and cell design. In addition, bipolar cells are capable of attaining high power densities (> 1 kW/kg). Such high power batteries must be cooled and do have a short life cycle. The drawbacks of these batteries are their high cost and relatively short life cycle (500 to 600 cycles max). These batteries have a flat discharge and can be designed for high-rate applications at the expense of a reduced cycle life. These batteries are used in tactical aircraft, submarines, satellites, and other aerospace systems. **Note:** *Countries with considerable expertise include Canada, China, France, Germany, and Russia.* Silver zinc primary reserve batteries are a well-established, mature technology used mainly for the military/aerospace market. These energetic batteries have a cell voltage of 1.8 V/Cell and energy density of 100–300 W hrs/kg and can be designed for high discharge rate/high power output applications. The battery has a wide temperature range (–40 to +60 °C), and cells can tolerate extreme stress (acceleration, vibration, and shock). The battery is compact and can be activated by physical forces (acceleration or shock/impact) or by electric valve or gas pressure (remote activation). The activation time is in milliseconds and is highly reliable. The primary market is military systems (missiles, munitions, and torpedoes). These batteries are quite expensive. **Note:** *Countries with expertise include Canada, China, Denmark, France, Germany, Israel, Japan, Russia, and the United Kingdom. In addition, India, Iran, and Pakistan could possibly have this technology and capability (speculative).*
Critical Materials	Electrolytic-grade silver foils, powders and fibers.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Reducing costs; recharging the battery. (The zinc electrode has limited the number of recharges, but research efforts continue.)
Major Commercial Applications	Commercial markets are limited because of very high costs.
Affordability	None identified.

RATIONALE

Silver zinc batteries are a highly reliable, energetic, compact, modular battery system capable of high-rate, high-power applications. These batteries have the potential to be enabling for high-energy weapon systems. Bipolar SiZn batteries can be used for space weaponry.

Military applications include tactical aircraft, missiles, ballistic missiles, satellites, munitions, torpedoes, submarines, and emergency pulsed-power systems.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●	China	●●●	Denmark	●●	France	●●●
Germany	●●●	India	●	Israel	●●	Japan	●●
Russia	●●●●	UK	●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The R&D for this technology is as follows:

- India: Limited. Their MIGs borrow this technology from Russia.
- Russia uses these batteries in their satellites.
- At one time, the U.S. Navy used these for a deep submersible and “rented” the silver from the U.S. Treasury.

DATA SHEET III-7.2. ELECTROSTATIC CAPACITORS

Developing Critical Technology Parameter	See parameter tables below
Critical Materials	Novel polymers, ceramics, diamonds, nitrides, glass-ceramic composites, ceramic-polymer composites, impregnants, and so forth.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Novel dielectric and impregnant development with concentration on increasing voltage breakdown strength and dielectric constant while decreasing the dissipation factor; superior capacitor device design, especially for high-voltage, high-energy density with rapid pulse delivery; and improved packaging for high-temperature, high-energy density capacitors with rapid, low-inductance delivery requirements.
Major Commercial Applications	Arc welding, oil/well drilling, medical defibrillators, high-power flash lamps, EVs, motor start circuits, and so forth.
Affordability	This technology will remain largely for military applications; however, cost can be reduced as other applications in the market become known.

Pulsed

Parameter	1999	Projected by 2010	Nature's Limit
Energy density (J/g)	0–7	10	
Capacitance (μF)	1–10	1–10	
Pulse rate (pps)	0.2	10–20	
Dissipation factor (loss)	0.005	0.0001	
Temperature range (°C)	–55 to +80	–55to +200	

Continuous

Parameter	1999	Projected by 2010	Nature's Limit
Energy density (J/g)	0–3	8	
Capacitance (μF)	1–10	1–10	
Dissipation factor (loss)	0.005	0.0001	
Temperature range (°C)	–55 to +80	–55 to +200	

RATIONALE

Essentially, few R&D dollars have gone into the pulse power dielectric/capacitor area since the Strategic Defense Initiative Organization (SDIO) days over 10 years ago. The current 1999 technology is basically what was achieved back in 1988. If ample financial resources are available from 2000 through 2010, significant progress can be made to enhance a critical component needed in our future military weapon systems.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	France	●●	Germany	●●●	Italy	●●
Japan	●●●	Korea	●●	Russia	●●●	Ukraine	●●
UK	●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Russia is a leader in pulse-power technology and reportedly has advanced pulse-power capacitor devices greater than our own. Japan, together with Germany, develops and makes nearly all state-of-the-art capacitor-grade dielectrics (polymers) for the world market.

DATA SHEET III-7.2. ELECTROCHEMICAL CAPACITORS

Developing Critical Technology Parameter

Electrochemical capacitors: energy storage/pulse repetition rate/back-up power, milliseconds. Parameters are listed for commercially available devices. Pulsed and CW requirements will demand similar capacitor parameters.

Pulsed			
Parameter	**1999**	**Projected by 2010**	**Nature's Limit**
Capacitance (F/cm^3)	2.6	5.2	
Series resistance (mohm)	4	1	1
Energy rensity (J/cm^3)	8	80	
Power rensity (W/cm^3)	80	320	

Continuous			
Parameter	**1999**	**Projected by 2010**	**Nature's Limit**
Capacitance (F/cm^3)	2.6	5.2	
Series resistance (mohm)	4	1	1
Energy density (J/cm^3)	8	80	
Power density (W/cm^3)	80	320	

Critical Materials

Electrode materials and electrolyte. One also must perfect packaging process along with materials development. Another area that remains unexplored is the development of power electronic converters matched to the unique requirements of these devices.

Unique Test, Production, Inspection Equipment

Production methods for these devices are well known. Testing of these devices can be accomplished with relatively simple equipment. Test procedures borrowed from traditional capacitor and battery testing methods can be used.

Unique Software

None identified.

Technical Issues

Energy density and power density; unfamiliarity among engineers; voltage limit of 3 V can be a limitation in some applications.

Major Commercial Applications

Advancements in power and/or energy density will enable more widespread use. Electrochemical caps will see aplication as a battery load leveler and a battery replacement (motor drive bus ride-through, UPS, portable electronics, automotive electronics). Presently used for memory backup.

Affordability

Cost is one limiting factor to the widespread use of these capacitors. Cost must come down to make these devices a viable commercial product. Current cost for Japanese capacitors is about $0.25/F.

RATIONALE

Niche applications for these devices at present state of the art; however, industry seems stalled at the present state of the art. To increase the market for electrochemical capacitors, improvements in energy density and power density will have to be achieved. Best electrochemical capacitors right now seem to be carbon electrode capacitors with an organic electrolyte. New assymetric electrode approaches are now surfacing and may significantly improve energy density.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Canada	●	France	●
Germany	●	Japan	●●●●	Russia	●●●
Sweden	●	Switzerland	●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States seems to be behind Japan in production of a low-cost, good-quality package.

DATA SHEET III-7.2. HIGH-ENERGY AND POWER DENSITY PULSED ALTERNATORS AND COMPULSATORS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (J/g)</td><td>1–2</td><td>10–20</td><td>100</td></tr>
</table>
Compulsators have been built at the University of Texas (UT) Center for Electro-mechanics that have demonstrated 1 J/g energy density. Every indication is that pulsed disk alternators (PDAs) could achieve the same or better performance; however, because of funding constraints, the Army was not able to build and test compulsators and PDAs at the same time after 1993.</td></tr>
<tr><td>Critical Materials</td><td>High-strength fibers for composites; high-temperature, tough, low-conductivity resins; high-strength, high-conductivity, low-resistivity conductor materiel; silicon carbide switches.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>• Test. High-power electromagnetic railgun facility at UT – Center for Electro-mechanics
• Production. Not in production as of this date
• Inspection. Vertical plane imaging (VPI) ultrasound and x-ray tomography; electrical property measurement; and rotor balancing.</td></tr>
<tr><td>Unique Software</td><td>EMAP-3D (electro-thermodynamics code).</td></tr>
<tr><td>Technical Issues</td><td>Energy storage technology sufficient to meet Army needs; advanced composites required for applications beyond 2010; advanced switching and control; system electromechanical efficiency; and thermal management. Vacuum must be maintained.</td></tr>
<tr><td>Major Commercial Applications</td><td>Launch of lightweight packages to LEO.</td></tr>
<tr><td>Affordability</td><td>Moderate.</td></tr>
</table>

RATIONALE

High-energy density devices are required for pulsed-power military applications, such as railguns, lasers, RF weapons, and so forth. One approach for delivering high-energy/power pulses is by using rotating machines, such as compulsators, PDAs, and homopolar generators. “Compulsator” is a term coined by UT and stands for “compensated alternator,” which is the generic name. Another machine design is a “pulsed disk alternator,” or PDA, which was developed in the late 1980s and early 1990s under Army Focused Technology Program for Electromagnetic Guns by Kaman Sciences.

> Air-core and Iron-core variants of these machines have demonstrated an ability to efficiently drive low impedance pulsed loads. Other advantages of these machines over PFNs [pulse-forming networks] include lower operating voltages, higher burst firing rates, and the ability to store a substantial number of shots in rotor energy. In addition, a wide variety of pulse shapes are possible and the current profile can be varied from shot to shot if needed (Walls, Pratap, Chryssomallis, 1997).

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●	France	●●	Germany	●●●
India	●●	Japan	●●	Netherlands	●
Russia	●●●●	South Korea	●●	Sweden	●
Ukraine	●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research is being conducted in the United States at UT, Austin.

SECTION 7.3—POWER CONDITIONING

Highlights

- Power conditioning is the process involved in modifying the source output to meet load characteristics.
- Voltage, current, time (pulse length), pulse shape, and frequency characterize power conditioning.
- Loads require power to be delivered in specifically shaped continuous or pulsed waveforms.
- Advanced weapons of precision and wide-area mass destruction, radar, countermeasures, and communications systems are enabled through next-generation-plus-high-energy electronics systems, including the prime energy sources.

OVERVIEW

Power conditioning is the process involved in modifying the source output to meet load characteristics. Such loads can include military and commercial applications. Military applications range from charging a battery or forming pulses for a weapon subsystem to electric motor drives. Two types of conditioning are defined by the amount of time over which power is supplied: continuous duty and pulsed or burst mode. To revisit, continuous duty is defined as power supplied to a load continuously, which, in this discussion, implies bursts lasting longer than 1 second (since semiconductor devices reach their thermal equilibrium in less than 1 second). Bursts lasting less than several seconds are considered pulsed power and generally have higher average powers. Pulsed power conditioning discharges a high-energy storage bank in a low repetition-rated burst mode (see Figure 7.3-1). For some applications, long pulses that last from several microseconds to seconds may be fed into a fast conditioning stage, which creates bursts with high power lasting from microseconds and femtoseconds.

Pulse conditioning subsystems are comprised of both discrete and transmission-line-type components. The circuit functions can be described by lumped element equivalent circuitry provided that the characteristic times of energy discharge are far longer than parasitic IRC (inductor, resistor, capacitor) time constants of any system component. These subsystems are intimately tied to the load, with efficiency and reliability often constraining the types of near-term solutions available. In the future, advanced component development and enabling new energy control topologies will permit considerable reduction in system size and mass for next-generation systems.

A considerable aspect of power conditioning is the pulse-forming functions. Pulse formation is dominated by the characteristics of the switches used. Switch performance is summarized and defined in terms of the following parameters:

- **Peak voltage** is the maximum voltage that can be applied while the switch is open without breakdown.
- **Peak current** is the maximum current reached by the pulse.
- **Charge** is the amount of current a switch can pass while conducting over a period of time.
- **Voltage drop** is the maximum voltage across the device when the current has reached its maximum value.
- **Current density** is the current per unit area of conduction.
- **Action** in a switch is the impact that occurs in a short interval of time because of a force associated with the high-energy pulse. The force introduces stresses and strains in the switch. These stresses can induce microcracks and fractures, which ultimately lead to device failure. If the value of the action exceeds the fusing capability of a solid-state device, failure is catastrophic. As a result, solid-state switches have to be operated at action levels well below their fusing limit. When devices are connected in parallel, including a fuse in series with each switch may be necessary (H. Singh, et al. 1999).

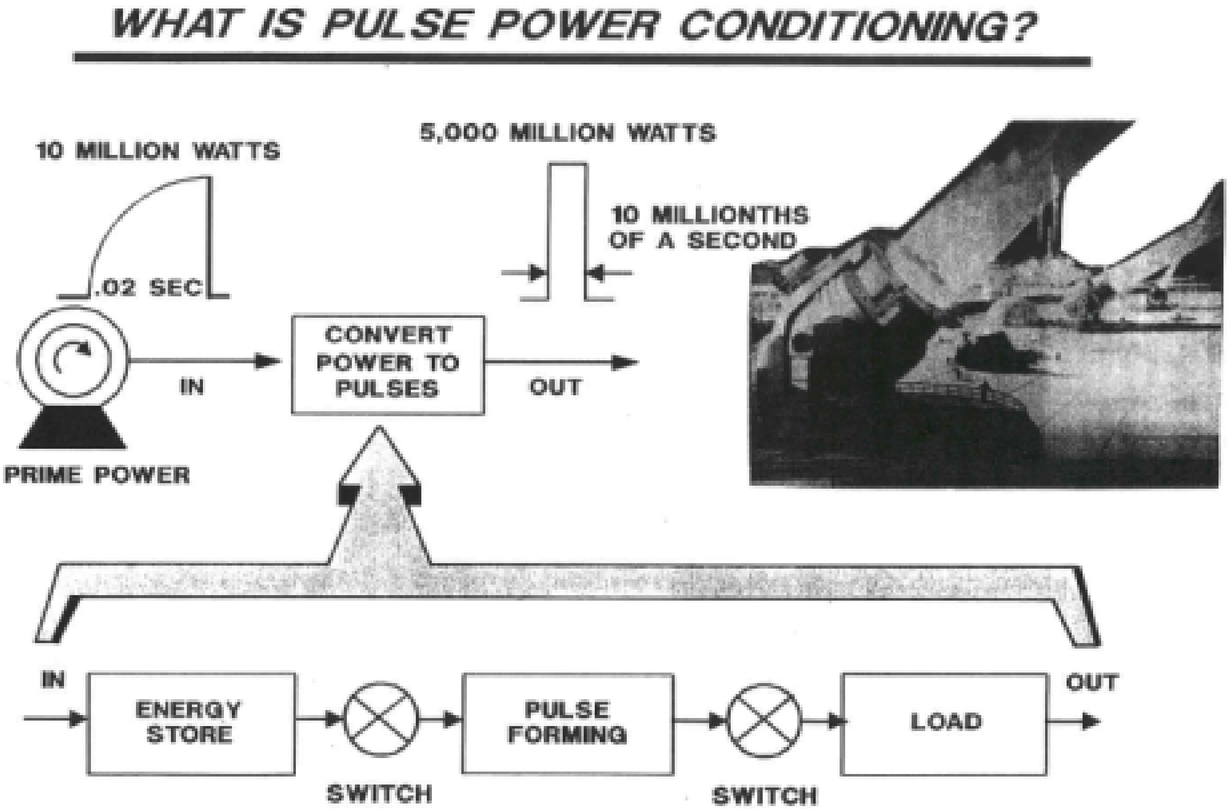


Figure 7.3-1. Pulsed Power Conditioning

- **di/dt** is the maximum rate of current rise that the switch can tolerate.
- **dv/dt** is the maximum rate of voltage rise that will not turn the switch on.
- **Thermal management** is the ability to remove heat energy generated by device.
- **Reverse blocking** is the peak voltage that can be applied across the device in reverse direction immediately after a high current in the forward direction.
- **System volume and mass** include the componentry: gate drives, protective drives, and so forth.
- **Life** is the predicted number of shots or pulses the device may deliver before failure.
- **Cost** is measured in dollars per switch.

Additional parameters include series and parallel operation, reliability, commercial availability, duration, and repetition rate.

RATIONALE

In the high-energy case, mainly for weapons applications, systems of average powers in excess of 100 MW for times of seconds to minutes are integrated with pulsed conditioning to create gigawatt class repetitive pulses of energy from milliseconds through submicroseconds. Voltages range from several kilovolts in the first case up through nearly megavolts in the latter case. This technology is used in commercial radar, smelting plants, and so forth. In addition, all aspects of the energy system demand significant technology base development at high risk. Thus, if needed, industry would possibly develop the capability but only if fully funded by the government. In addition, with the government technology investment base continuing to erode in militarily unique aspects of modern military systems, many industry senior management personnel feel that they are working as rapidly as possible to develop other customers, and, when these are in place, will be unwilling to redirect valuable internal expertise into government programs. There may emerge selected military applications, such as super energy radars, electronic countermeasures, and DEWs, that demand precisely conditioned electric energy of a class that has no direct foreseeable commercial or industrial application.

Power conditioning and pulse-forming networks are systems for the conversion of prime electrical energy into the necessary short pulses of electrical energy needed for loads such as DEWs and kinetic energy weapons (KEWs) and high power microwaves. Peak power, pulse shape, pulse duration, repetition rates, firing rates, silent watch, and system energy storage recharging times represent militarily critical performance parameters that transcend known commercial, industrial, or consumer applications. In addition, high-energy electronics, which are necessary to provide the power conditioning for a variety of military consumers, require parallel/series combinations of components to achieve reliability, fault tolerance, and graceful aging at performance levels an order of magnitude better than today's commercial standards.

Advances in technology for conditioning, regulation and distribution of power will be required to support advanced sensors, avionics, vehicle electronics (VETRONICS), and command, control, and communications (C3). These advances will address EMI, reliability, thermal management, packaging for high-energy densities, and so forth and will be equally critical to future commercial developments. Fielding smart weapons and remote unmanned sensors will also demand advances in high-energy density, high-energy military batteries.

Essential to the operation of almost all advanced weapons systems are well-regulated and high-energy density electronics systems supporting technology. This also includes technologies for continuous and pulsed systems, which are essential for a variety of industrial, commercial, and military applications. Typical examples of energy systems and components controlled specifically for nuclear and non-nuclear applications are identified in Part I, Section 15 of the 1996 Militarily Critical Technologies List (MCTL).

Electrical power systems, although absolutely essential to the operation of virtually all modern military systems, have been viewed as supportive rather than enabling. Where energy density drives enabling feasibility, they are clearly recognized as critical. While these are among the most noticeable applications, reliability, availability, maintainability, and energy quality constitute a significant portion of size, weight, and cost of military systems. In this context, prime energy and conditioned energy are recognized as critical elements for future military battlefield systems. Mission-compliant energy forms critical elements, with the application areas in systems fielded at present and in systems that will be fielded in the future.

Critical to future mission areas are affordable energy systems that enable stealthy mission compliance. This includes operating regimes that range from long life, continuous low drain (AA penlight cell energy levels for many weeks (submilliwatt energy levels at unattended locations) through terawatt peak power (single or limited burst duration) systems for DEW or nuclear electromagnetic pulse (NEMP) special effects weapons. Single-shot pulsed power at multi-megajoule energy-per-pulse levels for nuclear effect simulators is quite specific to that application and, being of little general technology applicability, is covered separately within the MCT Part III.

In general, conditioning can be divided into three areas: bus power conditioning, slow power conditioning, and fast power conditioning (NRC, 1993).

Bus Power Conditioning

Bus power conditioning takes the feed from one of the prime power sources into a conditioning stage where the voltage or frequency level is altered for optimum, reliable power distribution to other power conditioning stages.

Slow Power Conditioning

The slow power conditioning stage produces repetitive electrical pulses in the millisecond time frame. Switches, capacitors and transformers are the major components used.

Fast Power Conditioning

If required, particularly for weaponization, a final stage of power conditioning can be used to compress or transfer the millisecond-duration input pulses into microsecond, nanosecond, or picosecond pulses. This stage uses transmission lines/capacitors, switches, and magnetic devices as the primary components.

Figure 7.3-2 and Figure 7.3-3 display the trends for repetitive and microsecond power conditioning, respectively. In both figures, burst duty implies 100 sec "on" with several hours "off," while continuous duty indicates 24-hour operation. The barrier in Figure 7.3-3 is a performance barrier, which can be overcome with significant R&D.

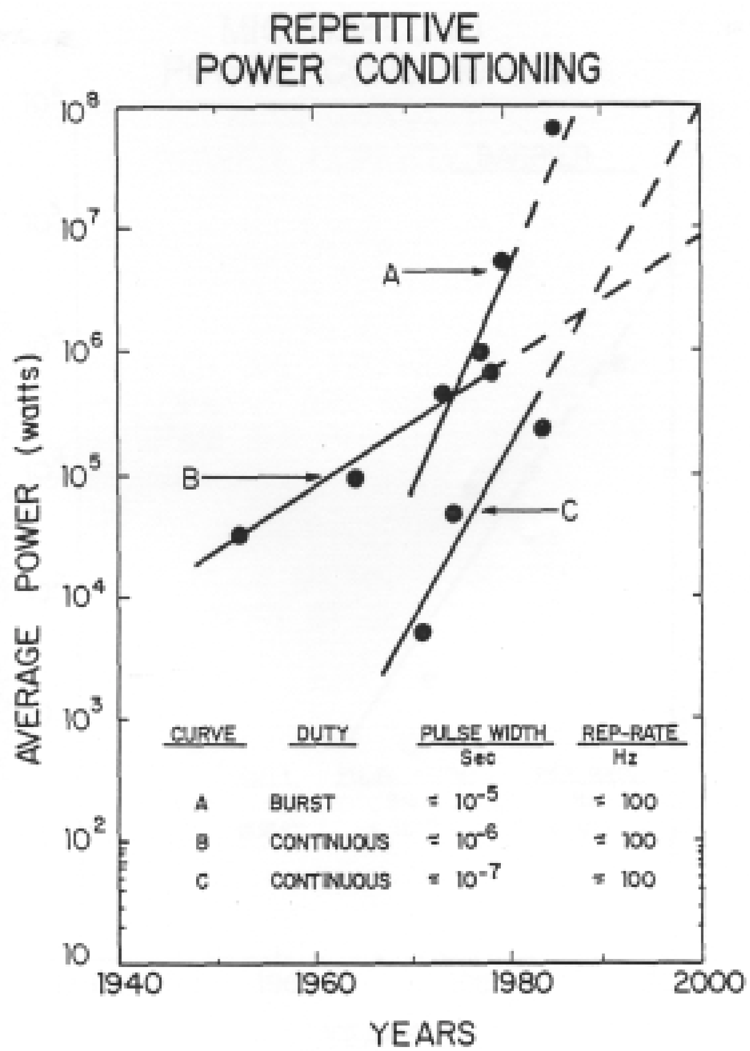


Figure 7.3-2. Repetitive Power Conditioning

To reiterate, power conditioning is the delivery of reliable and quality power, specifically pulsed power, where energy is provided in the necessary short pulses required by the load, such as weapons or other systems. For pulses of extreme short duration, special storage, switching devices, and packaging are required. Technologies for conditioning include inductors, resonant transformers, inverters, semiconductor diodes and switches.

In contrast to high-density conventional systems, pulsed and high-energy systems operate at average powers well above the 100-kW level. In this power regime, almost all applications are military, and many of these militarily unique applications project small-quantity procurements for the foreseeable future.

Since the ability to initiate actions without awareness by any adversary is becoming more significant, the need for stealthy land, sea, and air platforms is more important. With the exception of hydrocarbon-fuelled air vehicles, all others can be optimized for limited missions using electrical energy. Integration of hydrocarbon/nuclear fuels into future scenarios remains a possibility if signature management can be incorporated into initial designs.

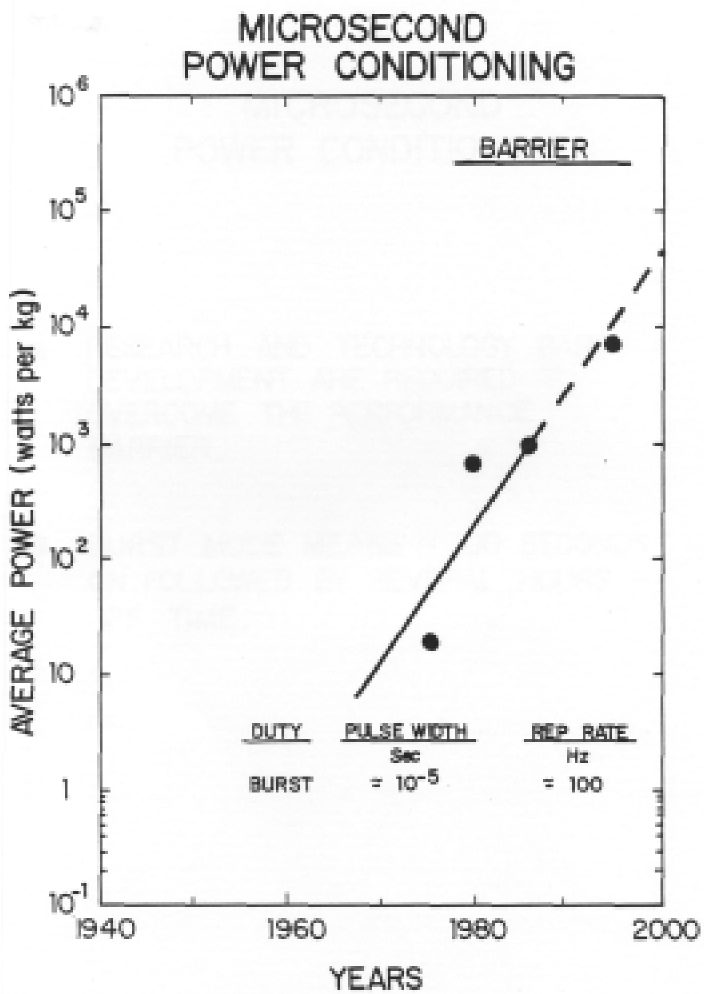


Figure 7.3-3. Microsecond Power Conditioning

For high-energy electronics systems for military systems, operating at multimegawatt average powers becomes viable only if available in very compact volumes.

Successful implementation will only proceed through direct DoD investment in high-energy switching, enhanced through international cooperative activities with our allies who have similar interests.

WORLDWIDE TECHNOLOGY ASSESSMENT

U.S. manufacturers are capable of meeting approximately 30 percent of the actual U.S. demand for high-power semiconductors. The remaining balance is imported from France, Germany, Japan, Sweden, Switzerland, and the United Kingdom. Several other countries, therefore, dominate the current power electronics market. Several U.S. manufacturers and the government are making headway towards expanding the U.S. market share in the high-power, high-temperature electronics area. Specifically, they are looking toward the potential future market in the Silicon-Carbide- and Nitride-based systems.

LIST OF TECHNOLOGY DATA SHEETS
III-7.3. POWER CONDITIONING

DATA SHEET III-7.3. LOW-REPETITION-RATE (LRR) AND BURST CAPACITORS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
LRR is approximately 1–10 pulses per second, < 5 percent duty cycle
Burst operation is approximately 100 sec on-time, < 5 percent duty cycle
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (J/kg)</td><td>1500-2500</td><td>5,000</td><td></td></tr>
<tr><td>Energy density (J/cc)</td><td>3–15</td><td>15</td><td></td></tr>
<tr><td>Number of shots (nominal)</td><td>1,000</td><td>1,000</td><td>1,000's</td></tr>
<tr><td>Pulse repetition rate (Hz)</td><td>0.1–10</td><td>< 100</td><td>100</td></tr>
<tr><td>Discharge efficiency (%)</td><td>85</td><td>95</td><td>99</td></tr>
</table>
Very LRR: 0.1 Hz, 1 kJ/kg, 100 shot, 75 kJ, 50 kV
LRR: 600 J/Kg; 104 shots; 50 kJ; 20 kV
Burst: 180 J/Kg; 100 Hz; 105 shots, 0.5 kJ, 40 kV
</td></tr>
<tr><td>Critical Materials</td><td>Dielectrics.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Winding machines.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Technical Issues</td><td>Discharge efficiency is an important characteristic for high-energy applications.</td></tr>
<tr><td>Major Commercial Applications</td><td>Commercial power.</td></tr>
<tr><td>Affordability</td><td>None identified.</td></tr>
</table>

RATIONALE

Some applications demand very high energy but only for very brief periods of time. Typically, LRR involves 1–10 pulses per second and a 5-percent-or-less duty cycle. This type of operation places extreme demands on capacitors (and other elements in the system) in terms of maximum voltage, current, and power that must be handled. The discharge rate and efficiency of different capacitor materials determines their application. For pulses on the order of tenths of a second duration, CDL capacitors hold great promise at high-energy densities. For pulses of millisecond or microsecond duration, polymer capacitors seem best suited. For very brief pulses (nanoseconds), ceramic capacitors are required. The United States is currently the technology leader in these areas.

Capacitors permit energy to be stored over a long period of time and then released as required over a very short period under controlled conditions. Burst operation involves high-power activity for intermittent periods. Typically, this might be 100 sec on-time and a 5-percent duty cycle. Peak levels are not as great as LRR, but the level is sustained for considerably longer periods and the limiting factor becomes heat dissipation. CDL and polymer capacitors are of most interest for this type of operation.

LRR and burst capacitors have the following military applications/general research objectives:

- **Military applications.** DEWs (laser, radar, RF, microwave, charged particle beam); electromagnetic and electrothermal launchers; electronic countermeasures/jammers; electromagnetic armor/active protection system; and mine clearing.
- **General research objectives.** higher energy density; greater discharge efficiency; increased number of shots; increased pulse repetition rate; graceful degradation; improved materials (films and foils, dielectrics, and impregnants); and improved manufacturing techniques.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	France	●●	Germany	●●●	Italy	●●
Japan	●●●	Korea	●●	Russia	●●●	Ukraine	●●
UK	●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The major foreign players by country and company or organization for this technology include:

- France: Thomson CSF, Institute of Saint Louis, Haefely Trench
- Germany: Siemens and university research
- United Kingdom: Syfer Technology.

DATA SHEET III-7.3. MEDIUM-REPETITION-RATE CAPACITORS

Developing Critical Technology Parameter	Medium repetition rate is nominally 100 Hz to 20 kHz **Parameter** | **1999** | **Projected by 2010** | **Nature's Limit** Energy density (J/kg) | 55–200 | 1,000 | Capacitance (μF/cm³) | 5–10 | 30 | Resistance (ohms) | < 0.01–0.005 | < 0.005 | Temperature (°C) | –55 to +80 | –55 to +125 |
Critical Materials	Improved materials (dielectrics, films, foils, insulation, impregnants); improved package (novel winding and casing design); improved manufacturing techniques (deposition limit for film).
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	None identified.
Major Commercial Applications	None identified.
Affordability	None identified.

Parameter	1999	Projected by 2010	Nature's Limit
Energy density (J/kg)	55–200	1,000	
Capacitance ($\mu F/cm^3$)	5–10	30	
Resistance (ohms)	< 0.01–0.005	< 0.005	
Temperature (°C)	–55 to +80	–55 to +125	

RATIONALE

Medium-repetition-rate capacitors have application in EW, communications, and laser radar. A major function of these capacitors is to reduce ripple in DC power supplies and to filter out unwanted higher frequencies in AC power systems. In both cases, frequency response and thermal management become critical issues. Conditioning for electric drive vehicles is another important application. Capacitors for filtering and power conditioning must be capable of medium frequency operation at high efficiency with low volume and weight (high-energy density) and equivalent series resistance (ESR). The ESR times the energy density is a figure of merit.

Medium-repetition-rate capacitors have the following military applications/general research objectives:

- **Military applications.** EW, communications, and laser radar.
- **General research objectives.** Higher energy density, higher specific capacitance, lower internal resistance, higher temperature operation, and graceful degradation.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	France	●●	Germany	●●●	Italy	●●
Japan	●●●	Korea	●●	Russia	●●●	Ukraine	●●
UK	●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The major foreign players by country and company or organization for this technology include the following: In France: Thomson CSF, Institute of Saint Louis, Haefely Trench; in Germany: Siemens and university research; and in the United Kingdom: Dowty.

DATA SHEET III-7.3. HIGH-REPETITION-RATE (AND CONTINUOUS) CAPACITORS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>High repetition rate is nominally greater than 20 kHz.
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (J/kg)</td><td>55–200</td><td>1,000</td><td></td></tr>
<tr><td>Capacitance (μF/cm^3)</td><td>5–10</td><td>30</td><td></td></tr>
<tr><td>Resistance (ohms)</td><td>< 0.01–0.005</td><td>< 0.005</td><td></td></tr>
<tr><td>Temperature (°C)</td><td>–55 to +80</td><td>–55 to +125</td><td></td></tr>
</table>
Continuous: 20 J/Kg, 100 Hz, 108 shots.</td></tr>
<tr><td>Critical Materials</td><td>Improved materials (dielectrics, films, foils, insulation, impregnants); improved package (novel winding and casing design); improved manufacturing techniques (deposition limit for film); and fault tolerance for high i^2t energy pulses that can be applied during conditions found under survivability situations.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Technical Issues</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>None identified.</td></tr>
<tr><td>Affordability</td><td>None identified.</td></tr>
</table>

RATIONALE

High-repetition-rate and continuous-operation capacitors have application in power conditioning, filtering, and inverters. A major function is to reduce ripple in DC power supplies and to filter out unwanted higher frequencies in AC power systems. In both cases, frequency response and thermal management become critical issues. Conditioning for electric drive vehicles is another important application. Capacitors for filtering and power conditioning must be capable of high-frequency operation at high efficiency with low volume and weight (high-energy density) and, in addition, very low internal inductance [equivalent series inductance (ESL)] and equivalent series resistance (ESR) to ensure high operational efficiency. The energy density divided by the product of ESR and ESL is a figure of merit.

High-repetition-rate capacitors have the following military applications/general research objectives:

- **Military applications.** Power conditioning, filtering, and Inverters (high repetition rate and continuous).
- **General research objectives.** Higher energy density; higher specific capacitance; lower internal resistance and inductance; higher temperature operation; and graceful degradation.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	France	●●	Germany	●●●	Italy	●●
Japan	●●●	Korea	●●	Russia	●●●	Ukraine	●●
UK	●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

DATASHEET III-7.3. DIELECTRICS FOR PULSE-POWER CAPACITORS

Developing Critical Technology Parameter	Develop superior dielectrics with greatly improved dielectric constant, voltage breakdown strength, dissipation factor, and discharge capability.
Critical Materials	Polymers, polymer-polymer composites, polymer-ceramic composites, nitrides, diamond like carbon (DLC), and polycrystalline diamond.
Unique Test, Production, Inspection Equipment	Superior winding machines critical to fabricating reliable device.
Unique Software	None identified.
Technical Issues	Discharge efficiency, tan delta, voltage breakdown strength, and temperature capabilities.
Major Commercial Applications	Utilities, oil/well drilling, medical defibrillators, aircraft, satellites, and lasers.
Affordability	None identified.

RATIONALE

Capacitors are a pervasive technology in every military and commercial application. Thousands of capacitors are used in military systems and are considered a critical link and a common area of failure. Future military systems will rely on the development of pulse power, high energy density capacitors. These devices will be the enabling technology. In the near term, the material that will make these pulse power devices possible will probably be a polymer or a polymer-based dielectric. The DoD will have to develop the dielectric materials since the superior performance required of these capacitor devices are unique to the military. The commercial sector typically does not require such high-performance devices under incredibly stressful repetitive conditions.

Consider the following about capacitors:

- They are the weakest link in all DoD pulse power electronics.
- They are the heaviest and most space-consuming component in all pulse power systems,
- They are the enabling technology for a multitude of military applications such as DEW, HPM, SBL, Directed Energy Advanced Technology Aircraft (DE ATAC), uninhabited combat air vehicle (UCAV), more-electric aircraft (MEA), electromagnetic/electrothermal launchers, and so forth.
- Reasons for failures: thermal overload and runaway, metal delamination, instability of dielectric properties within extreme environments, inadequate performance, high losses, and inhibiting size and weight, and so forth.
- Current energy densities are not sufficient. Major size, weight and volume reductions are imperative to field such systems.
- Advanced capacitor research for pulse power applications is not being actively pursued in the commercial sector without DoD support.

Several dielectric materials are currently being developed and may have the potential to improve our capability. These materials have improved electrical and/or thermal properties and may reduce the size, weight and volume of the current state of the art. Table 7.3-1 lists new materials that may be available in the future and indicates the research leaders. Other dielectric material developments exist, using a variety of approaches to energy storage and use. For example, the USAF has been particularly attentive to applications of DLC. As these technologies are developed further, they should be considered equally for critical military applications.

Table 7.3-1. Future Dielectric Materials and Leading Researchers (Source: F.P. McCluskey, 1997)

Dielectric Material	Commercial Source	Properties and Advantages
Polysilseqioxane	David Sarnoff Research Center	Good electrical properties up to 250 °C; superior to Kapton and Tezfel; can dip or spray coat
Teflon Perflouroalkoxy (PFA)	DuPont	Good mechanical and electrical properties to temperatures as high as 200 °C
Polyimide (PI)	DuPont	Small variations in dielectric loss to temperatures as high as 200 °C
Nomex 410, 418	DuPont	Aramid papers of synthetic aromatic polyamide polymer; chemically and thermally stable to > 220 °C; radiation resistant; 418 grade contains 50-percent inorganic mica platelets and is designed for high voltage
Deflator-PZBT Tetraflouro-PZBT	Foster-Miller, Inc.	High-temperature stability; low dielectric constant
PBO	Foster-Miller, Inc.; Dow Chemical	Very-high-temperature stability (300–350 °C), significantly exceeding the performance of Kapton and Tefzel
PBO-flourinated IPN	Foster-Miller, Inc.	High-temperature stability combined with resistance to flash-over
Organo-ceramic hybrid nano composites	Garth Wilkes; VPI	Resistant to ionizing radiation; high thermal; stability to > 200 °C
Polybenzimidazole-PBI	Hoechst Celanese	Linear thermoplastic polymer; excellent thermal stability and strength retention to > 300 °C
Flourinated PBO-PI	Hoechst Celanese	Combines possibility of polyimides with the high-temperature properties of liquid crystal polymers (LCPs)
Flourinated polyimides	Hoechst Celanese; Ube Industries/ICI America; DuPont	Readily available from Ube/ICI and DuPont; thermal stability exceeds Kapton and Tefzel
Voltex 450	Lydall, Inc.	Paper composed of aramid fiber and neoprene binder; low water absorption and high dielectric strength; thermally stable to > 200 °C
Thermoplastic PBO with hexaflourinated moieties	Material Lab; WRDC	Thermally processible; high-temperature stability (T_g > 380 °C)
PQ-100 polyquinolines	Maxdem	Thermally processible; available in several configurations; high purity
Polysiloxaneimides	McGrath; VPI	Resistant to ionizing radiation; high thermal stability
Poly-P-Xylene (PPX)	Nova Tran, Ltd.	Stable dielectric strength to temperatures as high as 250 °C; may lose some of its good mechanical properties when exposed to elevated temperatures for long periods of time
Flurocarbon-hydrocarbon polymers	DuPont	Readily available; high-quality films; moderate thermal stability
FPE Proprietary Aromatic Polyester	3M	Readily available, high-quality aromatic films useful up to 250 °C

The military has a great need for high-temperature capacitors, which would also have superior electrical properties above those offered on the market today. Since capacitors can be heated by use, by their environment, or by both, the many failures caused by overheating dramatically underscore the need for higher temperature capacitors. Capacitors for our planned future superior weapon systems will operate at such a rate that internal heat would surely cause immediate failure to today's devices—even without the addition of environment heat. With this knowledge, material development for a high-temperature film for use in capacitors was performed under the High Temperature Dielectric Program funded by the Air Force Research Laboratory (Propulsion Directorate)/Advanced Dielectrics and Capacitor Devices (AFRL/PRPE). The goal of this program was to develop a high-temperature capacitor film for maximum operating temperature of > 500 K (227 °C) and minimum operating temperatures of < 219K (–55 °C). The program was successful. FPE has 2X the voltage breakdown strength and 2X temperature capabilities of popular polymers used today, with a low dissipation factor superior to polycarbonate. No other types of high-temperature films possess both the electrical and thermal characteristics of Fluoro Poly Esther (FPE). Imation currently holds the patent rights to the FPE film.

Increased performance and smaller size has also been the main focus of current AFRL research in DLC dielectrics for applying high-energy density capacitors. DLC possesses the unique properties of high dielectric strength, high resistivity, high decomposition temperature, chemical inertness, radiation hardness, and good thermal conductivity. It has been demonstrated that very thin (0.5 µm) DLC films can be deposited directly onto smooth aluminum surfaces with good adhesion and that amorphous DLC films are highly flexible, making them suitable for the production of wound capacitor devices. The DLC capacitors are inherently rugged and will provide improved reliability and lifetime in all applications. AFRL/PRPE's development of this technology began in-house and continues now under an Air Force contract. Rolled DLC-coated aluminum capacitors can offer large volumetric efficiencies over the standard polymer types. The enabling technology has been demonstrated, and a prototype manufacturing system is currently being constructed. AFRL/PRPE owns a patent on the DLC capacitor technology.

AFRL/PRPE has also funded a successful program in cryogenic capacitors. The cryogenic ceramic capacitor research is unique and is essentially "one-of-a-kind." The cryogenic ceramic devices (operating at 77 K) have extremely high dielectric constants, low dissipation factors, and low relaxation times. The low temperatures ensure decreased resistivities of the metal components and lower dissipation factors and give much higher voltage breakdown strengths. In addition, liquid nitrogen is an inexpensive cryogen. This cryo-ceramic capacitor technology will have tremendous benefits for commercial and military ground-based and space-based systems. These devices also appear to be suitable for DC filtering applications and energy storage and quick pulse power energy delivery. The capacitors have shown repetition rate pulsing up to 250 pps, with energy densities approaching 6 J/cc. This cryogenic technology will provide capacitor devices that will alleviate many problems associated with utility uninterruptible back-up power systems. For the 77-K applications, a dielectric constant of 16,000 can be obtained with a dissipation factor of 0.002. Today, with the same dissipation factor, a typical ceramic provides a dielectric constant of only 2,000. The commercialization looks good for military and civilian markets. The worldwide UPS market is approximately $4 billion, of which the domestic U.S. market is $1.2 billion. CeramPhysics, Inc., holds the patent rights to the cryogenic capacitor technology.

Other new pursuits include the following:

- A novel metal-organic polymer through Foster-Miller, Inc., which may provide an energy density of 10 to 15 J/g
- A co-polymer solid solution blend dielectric through Lithium Power Technologies, Inc., with a potential energy density of 8 J/cc
- A synthesized polyimide-siloxane co-polymer through TPL, Inc. with a potential energy density > 4 J/cc.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●	Germany	●●●	Italy	●●	Japan	●●●
Korea	●●●	Russia	●●	Ukraine	●●	UK	●●
United States	●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Russia can produce diamond nanocaps. Additional companies pursuing advanced research for possible pulse power applications include DuPont Films, Sigma Laboratories, Inc., Custom Electronics, Inc., Aerovox, Dow Chemical Company, Maxwell Laboratories, Inc., and Physics International Company.

DATA SHEET III-7.3. CHEMICAL DOUBLE LAYER (CDL) CAPACITORS

Developing Critical Technology Parameter	Projected performance by 2005 for (pulsed) CDLs: • Discharge time of 1–300 sec • Charge time of 1–300 sec • Energy density ~ 5 W hrs/kg (inorganic electrolytes), 10–15 W hrs/kg (organic electrolytes) • Power densities > 10 kW/kg • Charge/discharge efficiencies ~ 80 percent at high rates and 98 percent at low rates • Cycle life >100,000 cycles at 100-percent depth of discharge • Charge and discharge current densities > 100 Å • Temperature range –55 to +85 °C, 98-percent-plus reliability. CDLs, which are produced in modular units and scalable in size for meeting power load requirements, are designed for HEVs. Most likely serially assembled in banks of capacitors to meet selected power loads. Produced mostly in cylindrical configurations out of materials that provide very large active surface areas for the electrode/electrolyte interface to support the generation and storage of ions along the surface.
Critical Materials	Improved organic and inorganic electrolytes with higher breakdown voltages; improved microporous polymeric separators; and improved active carbon materials with extremely large active surface areas (over 3,000 m/g) (e.g., carbon nanotubes and glassy carbon fibers).
Unique Test, Production, Inspection Equipment	CY91 R/T: CDL scaling verified to > 100-kJ levels R: intrinsic break down-laminates, impregnants and model sections T: continuous: > 30 J/Kg; 20 kHz; > $l0^8$ cycles; 2 F; 1.5 kV; inverter.
Unique Software	None identified.
Technical Issues	Develop improved electrolytes with greater conductivity, ionic transport, and higher breakdown voltages. Also, develop improved polymeric separators that can tolerate high voltages over thousands of cycles.
Major Commercial Applications	HEVs, automotive ignition systems, portable electronics, computers, telecommunications, avionics, remotely controlled actuators, and emergency back-up power supplies. **Note:** *To date, very few CDL products are on the marketplace.*
Affordability	None identified.

RATIONALE

CDL capacitors are also known as ultra-capacitors, super capacitors, super-caps, and electric double layer capacitors. This type of energy storage represents a rapidly emerging and promising technology that can be used to develop high-power energy storage systems that are durable, reliable, affordable, compact in size, lightweight, and capable of having a long service life (over 100,000 cycles). The system is robust and can tolerate extreme temperatures (–55 to +85 °C), severe shock, vibration, and acceleration. This system can survive extreme battlefield conditions and is an attractive energy storage device/system for use in combat vehicles, robotics, weapon systems, electromagnetic armor, portable electronics, and soldier-support systems. CDL capacitors are safe, use low-cost environmental-friendly materials, can be quickly charged and discharged, and produce very high current and power densities. This technology is being is being driven by automakers developing energy storage devices for HEVs.

CDLs are an attempt to produce a robust, compact, and affordable energy storage device with a high-power density, quick discharge/charge capability, and long cycle life (100,000 cycles or ~ 10 years). This system would be safe, environmentally friendly, sealed, and maintenance-free. It would also tolerate abuse.

Compared with conventional capacitors, CDLs have a greater energy and longer cycle life but have a much slower discharge and charge rate and a lower power density.

Military applications for CDLs include automotive ignition systems, EVs, portable electronics, soldier support systems, avionics, aerospace systems, missiles, remotely controlled actuators, and possibly electromagnetic armor and high-energy weapon systems.

CDLs can augment lead-acid starter storage batteries in combat/transport vehicles and have also been demonstrated in foreign HEVs and solid-state automotive ignition systems.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	China	●●	France	●●●●
Germany	●●●●	Italy	●●	Japan	●●●
Netherlands	●●	Russia	●●●●	Switzerland	●
UK	●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

To date, CDL capacitors have been demonstrated in prototype EVs in Japan and Europe to provide burst power for acceleration and hill climbing. In addition, Subaru (Japan) and a Russian firm produce CDLs to supply boost power for starting heavy-duty vehicles, especially in cold weather.

Centers of foreign expertise for CDLs include production and marketing in Japan, France, and Russia. Russia may now be using CDLs in military vehicle ignition systems and in serially produced silent military HEVs. Considerable foreign research involves conductive polymers, gel-ionics, rapid-ion transport systems, and advanced carbon nanomaterials.

Presently, the leaders in CDL technology include Japan, France (SAFT), Germany, Russia, and the United States (Maxwell, Aerovox).

In March, 1999, LANLachieved 2.7 million charge/discharge cycles.

DATA SHEET III-7.3. SOFT SWITCH INVERTERS

Developing Critical Technology Parameter	<table><tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr><tr><td>Power density (MW/m^3)</td><td>5</td><td>20</td><td></td></tr><tr><td>Switching speed (kHz)</td><td>20</td><td>100s–1000</td><td></td></tr></table>
Critical Materials	SiC Wide Bandgap (WB) materials.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Integrated microprocessor controls.
Technical Issues	Topology, EMI reduction, and switch safe operating area (SOA).
Major Commercial Applications	Computers, high-speed transportation (Maglevs), and EVs.
Affordability	None identified.

RATIONALE

Power switches are an integral part of any power converter circuit. Unfortunately, they are also the major source of power dissipation in the circuit. This power dissipation is caused by two features. One is conduction voltage drop in the switch while the switch is conducting. Some devices have lower conduction drops (MCT, BJT) (hence, lower conduction losses), while other devices have medium to high conduction drops (IGBT, MOSFET) (hence, medium-to-high conduction losses). The other cause of energy dissipation in a power switch is the dynamics of the switching. Switching of current in the presence of a switch voltage and vice versa, commonly referred to as hard switching, causes power losses in the switch. The switching loss increases with the switching frequency. To reduce the switching loss very fast devices are built. These devices have very fast turn-on and turn-off characteristics. However, high di/dt and dv/dt associated with this fast switching increase stresses on the switch and causes EMI. To alleviate the difficulties associated with hard switching, the concept of soft switching was introduced. The main underlying principle in soft switching is to switch the power device at the instant when the switch current is zero, known as zero current switching (ZCS), or switch the device when switch voltage is zero, known as zero voltage switching (ZVS). This way both the switching loss and switch stresses can be reduced (Source: Ehsani, 1997).

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●●	Germany	●●●	Japan	●●●
Russia	●●●	Sweden	●●●●	UK	●●●●
United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D

In the United States, the Oak Ridge National Laboratory (ORNL) is developing this technology.

DATA SHEET III-7.3. HIGH-TEMPERATURE SUPERCONDUCTING (HTS) WIRES

Developing Critical Technology Parameter

Parameter	1999	Projected by 2010	Nature's Limit
BSSCO critical current density (kA/cm^2)	70 (77 K,SF,short)	70 (77K,SF,long)	
BSSCO conductor length (m)	1,000 (Jc=15 kA/cm^2)	> 1,000	
BSCCO engineering current density (kA/cm^2)	13 (77 K,SF,long)	35 (77 K,SF,long)	
YBCO critical current density (kA/cm ^{2})	2,000 (77 K,SF,short)	1,000 (77 K,SF,long)	> 10,000 (77 K,SF)
YBCO conductor length (m)	1	100's	
YBCO engineering current density (kA/cm^2)	10 (77 K, SF)	50 (77 K,SF)	

Critical Materials	Reduction in the Ag content of the BiSrCaCuO conductor to reduce cost of the cable and development of YBCO-coated conductor architecture [non-magnetic substrates, buffer layer(s)].
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Grain boundaries and interconnectivity for BSSCO and YBCO.; long-length production of YBCO with high current densities; and increase in thickness of YBCO and decrease in thickness of substrate.
Major Commercial Applications	Power cables for utility transmission lines; fault current limiters; smaller, more efficient transformers; and efficient, compact motors and generators.
Affordability	Ag sheathed BiSrCaCuO cable is expensive because of the large amount of Ag needed. YBaCuO wire is in development and may offer a less expensive alternative and the ability to maintain high current densities in large magnetic fields at 77 K.

RATIONALE

Copper-based equipment generates waste heat and resistive loss, has limited capacity for carrying large currents, and is heavy. HTS wires are the converse. They generate minimal heat, may carry large currents, and are much lighter. Superconductivity offers significant theoretical advances in capability and performance for several power applications. Low-temperature superconducting (LTS) wire is fairly well-developed by U.S. and Japanese companies and is being applied to magnetic resonance imaging (MRI) medical imaging and other systems (mechanical and magnetic). LTS, however, is not currently a candidate for battlefield use because it requires liquid helium, which involves unacceptable logistics and handling problems. Recent advances in closed cycle refrigeration systems, however, may allow LTS in certain vehicle applications (primarily Navy). HTS wire offers potential in rotating machines (and several other areas) if processing techniques can be developed that allow practical lengths of HTS wire to be produced. Recent advances by U.S. and Japanese firms offer promise that high-current cables of high-temperature (77 K) superconductors can be fabricated and could have future practical application in DEWs and KEWs if the thermal management requirements can be met.

High-temperature superconductivity has received a great deal of public attention, and, in many cases, exaggerated or premature claims have been made concerning the revolutionary changes it will effect. For the most part, high-temperature superconductivity is still in the early research stage. However, significant advances have occurred in the area of HTS wires. High-current cables consisting of high-temperature (77 K) superconductors are being fabricated in kilometer lengths. This may allow practical application of HTS in DEWs and KEWs, and all-electric vehicles. HTS is identified in the DoD Army Science and Technology Master Plan (ASTMP) as having potential for a significant breakthrough in EV propulsion. Presently, the drivers for this technology are in commercial power, specifically in coils and magnets, fault current limiters, transformers, and superconducting underground cables for power transmission, especially in urban areas needing increased power capacity (see Figure 7.3-4).

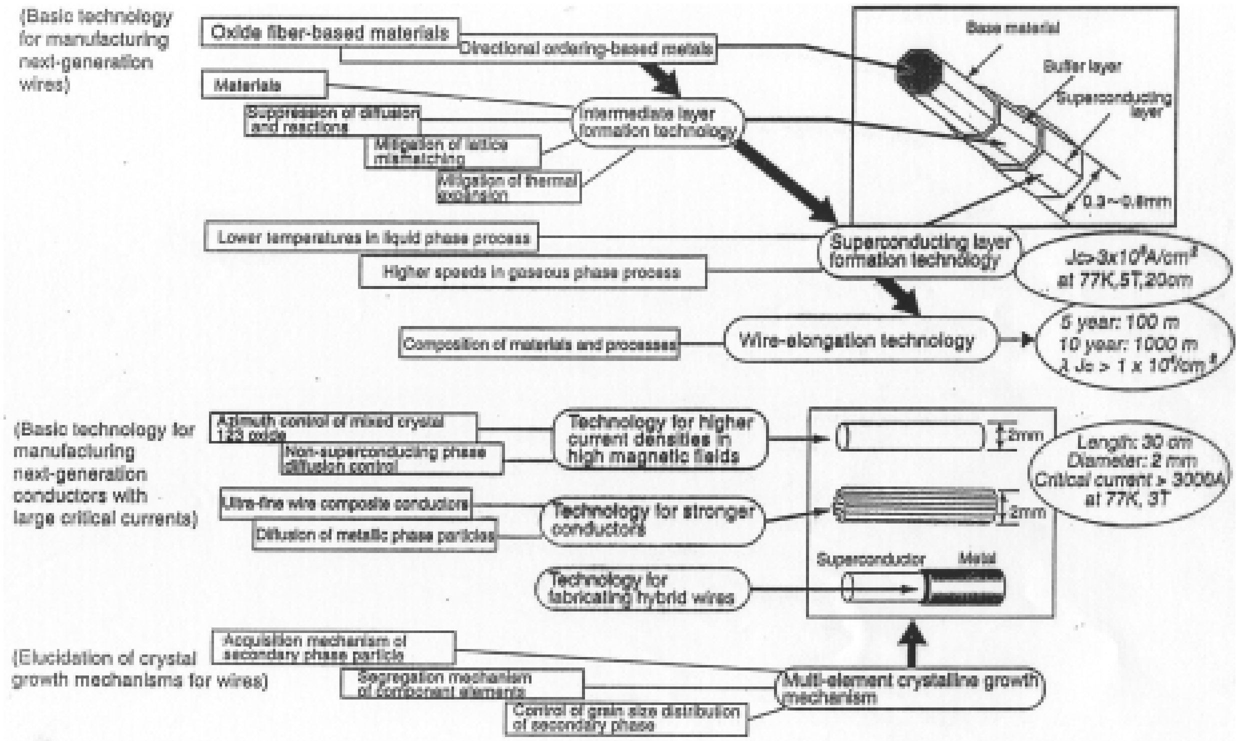


Figure 7.3-4. Basic Research Challenges on Superconducting Wire Materials

WORLDWIDE TECHNOLOGY ASSESSMENT

Europe ●● Japan ●●● United States ●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Japan and the United States are currently laying test cables for use by the public. European leaders include France, Germany, Italy, and the United Kingdom.

DATA SHEET III-7.3. PULSE TRANSFORMERS

Developing Critical Technology Parameter	Fast charging: 0.1–1 µs. 1.5 MV; 20 Hz; 1.5 kJ (Air Core). 0.8 MV; 100 Hz; 27 kJ (Iron Core). Lightweighting by –10 X required: burst and continuous operation. Vacuum operation in some systems. Move to higher frequencies is counter to insulation strength trends. New materials needed. Space compatibility and traceability, reliability, maintainability, and availability (TRMA) require validation. Capacitor charging: 2 MV; 100 kJ; 20–100 µs; 1,000 Hz; 1,000-sec burst; 5-percent duty factor. Flat top: 1–3 MV; 100 kJ; 0.5–20 µs; 1,000 Hz; 1,000-sec burst.
Critical Materials	Core material (composites), ferrites. High T operations, Wire technology, HTS Magnetic materials/insulation: • New, low loss Metglas (2X) • High stress grading insulation with molecularly designed polymers (5X) • Near ultimate (25–30 kV/mil) insulation • Vapor mist.
Unique Test, Production, Inspection Equipment	Purity of raw materials/device design.
Unique Software	None identified.
Technical Issues	Need to minimize stray elements and develop manufacturing technology (magnetics, core types (including air), windings and close tolerance fabrication). Power flow: Litz wire replacement with composites or new winding topologies to reduce power loss. For pulse transformers, higher peak current (2X). Fault management: Fusing and optimum conductor topologies/materials (R/T).
Major Commercial Applications	Air pollution control, food processing, water purification, rock breaking, multikilohertz lasers, and research accelerators.
Affordability	None identified.

RATIONALE

Pulse transformers, or pulse-charging transformers, are a power-conditioning device and are used when high-voltage gains and efficiencies are required. Essentially, they are employed when one needs to tailor voltage to a load.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●●	France	●	Germany	●●●
India	●●●	Japan	●●	Sweden	●●
Switzerland	●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States is superior to all others in high-action specialty transformers for weapons. Potential contributors include DuPont, Pennwalt, and 3M. This technology has little commercial value.

DATA SHEET III-7.3. WIDE BANDGAP (WB) SEMICONDUCTORS

Developing Critical Technology Parameter	WB semiconductors are an enabling technology for many military systems (e.g., space-based observation and weapons platforms; ground-based systems, such as DE, radar, and laser systems). Further, these systems require electronics that can tolerate higher temperature operation, thereby eliminating bulky and heavy cooling systems. WB semiconductors can also be used for power conditioning and pulse-forming network applications for all of the aforementioned systems and platforms, which are designed to be employed over the next 20 years (10- to > 100-kV-type levels; discrete high current devices > 1,000 Amps; high operating junction temperatures > 500 °C; reliable device operating temps > 450 ºC; discrete device blocking voltages > 5,000 V; and power switching frequencies > 200 kHz for power levels above 10 kW and > 500 kHz for power levels from 1–10 kW).
Critical Materials	WB semiconductor materials include SiC, III-Nitrides, BC, diamond, and TiC and thermally stable dielectric materials with low dielectric constants and large field strengths; low resistance; high thermal stability packaging; direct bended copper (DBC), aluminum indium nitrade (AIN)-based materials; low resistivity (< 10-6 Ω-cm^2); thermally stable (> 600 °C) ohmic; and Schottky contact technology.
Unique Test, Production, Inspection Equipment	Surface mount technology; electro-deposition processes; large volume expitaxial reactors; large volume substrate production facilities for WB semiconductor materials such as SiC, III-Nitrides, BC, diamond, TiC; and thermally stable dielectric materials with low dielectric constants and large field strengths. Material issues: micropipe and other defect effects, and large area growth. Fabrication issues: dry etching, ion implantation, oxidation, ohmic contacts. Device design Issues: transistors, thyristors, dynistors, insulated gate bipolar transistors (IGBTs), metal-oxide semiconductor field-effect transistors (MOSFETs), and MOS-controlled thyristor (MCT) design. Growth of materials with near-zero defects.
Unique Software	None identified.
Technical Issues	The growth of large area, defect-free material is critical. The critical factors driving the maturation of this technology are primarily materially based. Present day limitations include material quality and fabrication issues (etching, contact formation, ion implantation doping, acceptor doping, and stable dielectrics with low interface state defect densities). Europeans are claiming a safety issue (biological effects) above 500 kHz. Research objectives should include device design (thyristor, diodes, transistors, MOSFETs, IGBTs, MCT); current density and action; maximum voltage; operating temperatures; forward voltage drop; and switching speed.
Major Commercial Applications	High-power utility electric power distribution, high-frequency tranceiver for personal communication; opto-electronic applications for visible emitters [blue and green light emitting diodes (LEDs) and laser diodes] with significantly reduced power consumption.
Affordability	None identified.

RATIONALE

SiC material properties offer the potential to develop devices with much higher (10-fold increase) voltage capability and much lower (by a factor of 100) power dissipation (at equal currents) than more conventional silicon devices. SiC's potential for making devices with higher operating temperatures (500 °C) makes it superior where cooling system size and weight are important and where very high-power handling capability or higher temperature operation is required. Near-term SiC Schottky diode rectifiers may provide higher voltage, faster switching, higher temperature, and lower loss replacements for the widely used silicon rectifier diodes.

The performance potential of the WB semiconductor materials for power semiconductor switching applications far exceeds that of present-day Si technology. Potentially realizable goals include 100X lower on-resistance and 10X reductions in switching losses.

SiC devices are expected to be able to withstand temperatures in excess of 500 °C in contrast to a temperature of 150 ºC for silicon. This significantly changes thermal management constraints when the device is integrated into a system (i.e., using engine oil to cool a switch).

Military applications include EV drive, inverters, power conditioning, pulsed power for electric guns, and DEWs and KEWs for programs such as All-Electric Ship, More-Electric Aircraft, All-Electric Main Battle Tank, and so forth.

WORLDWIDE TECHNOLOGY ASSESSMENT

Finland	●●●	France	●●●	Germany	●●●●	Israel	●
Japan	●●●●	Russia	●●●●	Sweden	●●●●	Switzerland	●●●●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The major foreign players by country and company or organization for this technology include:

- Japan: all major companies (more than 25)
- Russia: Loffe Physical Technical Institute (St. Petersburg) and several others
- France: Numerous locations performing research
- Sweden/Switzerland: Asea Brown-Boveri (ABB), and the Industrial Microelectronics Center (IMEC)
- Germany: Siemens (devices and bulk substrate material) and others.

In the United States, the Army Research Laboratory (ARL) Pulse Power/Rutgers has demonstrated 1,000 V 6H Schottky diodes for high-power field-effect transistors (FETs) and have fabricated and tested functioning 6H silicon carbide thyristors. Several groups have demonstrated SiC MOSFETS up to about 180 V and 0.5 Amps. Evidence has recently been reported that micropipe defect-free 6H material can be grown. Growing material with low defects over the large area required for power devices is an important challenge.

DATA SHEET III-7.3. DIAMOND SEMICONDUCTOR SWITCHES

Developing Critical Technology Parameter	These switches may have the following capabilities: operation at average power levels greater than 100 kW, duty cycles greater than or equal to 0.01, peak current density in pulsed mode greater than 100,000 A/cm^2, voltages greater than 100 kV, rise times less than 1 ns, and internal inductance < 1 nH/A. When used in pulse-forming networks for narrow-band HPM, they are required to deliver at least 1 MJ per pulse. They also exhibit radiation hardness for operation in a nuclear environment.
Critical Materials	These switches and related contacts and leads must be capable of operating at high temperatures because of the intrinsic energy dissipation inherent in switches. This would suggest materials that have high specific heat and high conductivity.
Unique Test, Production, Inspection Equipment	Equipment that can fabricate a system of switches that provide the required synchronism better than 1 ns for parallel operation.
Unique Software	Software that can support the fabrication process.
Technical Issues	These switches are applicable for both narrow-band and WB HPM applications. To produce peak powers greater than 10^{12} W, several switches operating in parallel and without jitter are required. Technical issues are concerned with meeting the operating requirements while making the devices compact and capable of dissipating the heat.
Major Commercial Applications	So far, the only applications for this technology have been military. Potential commercial opportunities include applications in electric power, the automotive industry, and electric drives.
Affordability	Too early to establish. Could be a big issue.

RATIONALE

Switches that meets the projected operational requirements of both ultra-wideband (UWB) and narrow-band HPM systems are essential for building a viable weapon system. Diamond semiconductor switches show promise for meeting the requirements.

WORLDWIDE TECHNOLOGY ASSESSMENT

Germany	●●	Japan	●●●
Russia	●●●	UK	●●
United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

DATA SHEET III-7.3. MOS-CONTROLLED THYRISTOR (MCT)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>Research objectives: higher voltage, current, action, and current density.
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Action (A^2 - sec)</td><td>0.25</td><td></td><td>1</td></tr>
<tr><td>Switching speed (kHz)</td><td>50–200</td><td>250</td><td>MHz</td></tr>
<tr><td>Current density (A/cm^2)</td><td>400–500</td><td>500</td><td>> 500</td></tr>
<tr><td>Max blocking voltage (kV)</td><td>2–3</td><td>4</td><td>5</td></tr>
<tr><td>Max peak current (kA)</td><td>0.15–1.2</td><td>1.2</td><td></td></tr>
</table></td></tr>
<tr><td>Critical Materials</td><td>High-temperature materials.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Production of devices on SiC and other high-temperature-capable substrates.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Technical Issues</td><td>Reduce forward voltage drop in on-state; increase maximum operating voltage and current and SOA; and improve materials doping and processing.</td></tr>
<tr><td>Major Commercial Applications</td><td>None identified.</td></tr>
<tr><td>Affordability</td><td>None identified.</td></tr>
</table>

RATIONALE

The MCT is a high-power, high-frequency, low-conduction-drop, rugged device that seems to be the leader for medium- and high-power applications. It offers the power handling capability of a near-ideal thyristor but is controlled in turn-on/turn-off by an MOS transistor acting as a gating device. In addition to fewer losses and higher switching speed, MCT offers lighter weight, smaller space, and lower operating costs. It can be used in inverters, motor controllers, and power controllers but may also have application in pulsed-power systems. The MCT, because it can handle higher voltages, operate at higher temperatures, and offers higher current density (which means a smaller package is required), may take over the markets now dominated by gate turn-off thyristors (GTOs) and IGBTs. Devices being sold now for industrial applications can control up to 120 kW. Utility-scale MCTs are now available.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●●	Germany	●●●●	Israel	●●
Japan	●●●●	Sweden	●●●●	Switzerland	●●●●
United States	●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

For this technology, the major foreign players by country and company or organization include: In Japan, Mitsubishi, Toshiba, and numerous other companies; in Germany: Siemens; and in Switzerland: ABB.

The U.S. government's Technology Reinvestment Program (TRP) recently awarded a 2-year grant to Harris Corporation and EPRI for R&D to develop a new generation of power electronic building blocks (PEBBs). Based on MCTs, these will have broad application in power conversion and conditioning circuits for commercial and military applications.

In Japan, MCTs are also referred to as MAGTs (MOS-Assisted Gate Thyristors).

DATA SHEET III-7.3. MOS TURN-OFF THYRISTOR

Developing Critical Technology Parameter	<table><tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr><tr><td>Turn-off time (μs)</td><td>10's</td><td>< 10's</td><td></td></tr><tr><td>Turn-off gain</td><td>4–5</td><td>100's</td><td></td></tr></table>
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Monolithic processing.
Unique Software	None identified.
Technical Issues	Integration of MOS with thyristor wafer; noise generation.
Major Commercial Applications	Power switching, power conditioning.
Affordability	None identified.

RATIONALE

The MOS Turn-off Thyristor will replace the GTO because of its increased turn off time. GTO turn-off times are currently hundreds of microseconds where the MOS Turn-off Thyristors are currently tens of microseconds.

WORLDWIDE TECHNOLOGY ASSESSMENT

Germany	●●	Japan	●●
Sweden	●●●	Switzerland	●●●
UK	●●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

DATA SHEET III-7.3. INTEGRATED PULSE-FORMING NETWORKS (IPFNs) AND CAPACITORS

Developing Critical Technology Parameter	Energy Discharge IPFN: • Material-limited; > 100 Hz prf; burst/continuous duty • 15–20 kJ/kg energy density IPFN at 15–20 MJ/m^3; multimegajoules per unit, including switching and inductors. Filter and inverter capacitors: • Material-limited: > 10 kHz prf; burst/continuous duty • > 10 MVA/kg power density installed in case.
Critical Materials	Materials with a high dielectric constant and strength.
Unique Test, Production, Inspection Equipment	Winding machines.
Unique Software	None identified.
Technical Issues	Packaging.
Major Commercial Applications	Medical industry, food sterilization, and air pollution control.
Affordability	Depends on availability and cost of dielectrics.

RATIONALE

The following approach should be followed to satisfy the requirements.

Road Map

- Manufacturing technology: plastic, and coaxial metal cans for > 1 kJ; clam-shell and Scyllac size (114 kg) units for > 1 MJ; close tolerance fabrication
- Insulating films: new molecular polymers for lower losses and higher breakdown (10X) inorganic films (e.g., mica)(2X)
- Impregnants: permittivity match/miss-match confirmation; thermal and field induced degradation/control (5X)
- Power Flow: assess impulsive limits and charge/discharge techniques to minimize inductance and losses (2X decrease overall; present range 20–60 nH)
- Fault management: fuzing and optimized conductor topologies/materials (R/T)
- Low loss electrolytes (5X)
- Metallized dielectrics and current conductors developed for maximum current density (2X).

Milestones:

CY99 LRR: 2 kJ/kg; > l-Hz rep. rate; > 10^3 shots: > 250 kJ/unit; 10–20 kV; low-loss, < 5 percent

Burst: 0.5 kJ/kg; 100 Hz; > 10^5 shots; 10 kJ; 50 kV

Continuous: 0.1 kJ/kg; 100 Hz; > 10^{10} shots; 0.l kJ; 50 kV.

CY01 LRR: > 5 kJ/kg; > 10-Hz rep. rate; > $l0^4$ shots; > 0.5 MJ/unit; l0–20 kV; low-loss, < 5 percent

Burst: > 2 kJ/kg; > 10-Hz rep. rate; > 10^3 shots; 50 kJ; 50 kV

Continuous: > l kJ/kg; 100-Hz rep. rate; > 10^8 shots; l0 kJ; 50 kV.

New Programs

CY02 T: TRMA feasibility established (all categories)

T: Operability and survivability issues satisfied and verified (discharge capacitors and IPFNs)

T: MMT demonstrated for high TRMA/volume production feasibility

T: > 2 kJ/kg validated for electrolyte and CDL.

CY03 > 5–15 MJ/m^3; 5–10 kJ/kg (validated for energy discharge IPFNs and filter/reservoir capacitors); energy density is application driven over the ranges specified here by the system's designers.

CY05 R/T: LLRC 15–20 kJ/kg; > 10-Hz rep. rate; > 10^4 shots;> 1 MJ/unit; 10–20 kV at high TRMA (> 99-percent confidence) in IPFN to yield 10–15 kJ/kg integrated energy density; specific densities are application specific

R/T: Continuous > 60 J/kg; > 50 kHz; > 10^{10} cycles; 10 °F; 5 kV; inverters; all other issues above satisfied

R/T: CDL > 10,000 J/kg; > 10 Hz; > 10^4 shots; > 50 kJ; 5 kV at high TRMA (> 99-percent confidence).

The materials component is not included in this programmatic framework. This is a serious challenge since costs to develop new thin insulating films could easily exceed $100 M/year unless industry can be persuaded to invest because of commercial, high volume spin-off markets.

In this program, the out-years assume a shift from the high-energy capacitor development into the IPFN arena, including additional costs for the switching development if an early transition to solid-state switching is warranted. The true costs to develop multimegajoule, high i^2t switches of this millisecond-duration current conduction time is likely to exceed $250 M through the prototype level unless high-reversal capacitor elements can be developed that negate the need for clamping diodes and fuses.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●	Germany	●●
Japan	●●	UK	●●●
United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

R&D for this technology is being conducted as follows:

- **Energy discharge and filters**. Aerovox, High Energy Corporation, Maxwell Laboratories, Condenser Products, Capacitor Specialists, and GE
- **Inverters.** Capacitor Film Inc., Maxwell Laboratories, and High Energy Inc.
- **Mica.** Custom Electronics, Cera-Mite Corporation, Chenelec Company, Stanley Electronics, and Corona Film, Inc.
- **Ceramic.** TDK, Murata, Kemet, High Energy, and AVX Ceramics
- **Electrolytic.** Sprague, Philips, Siemens, Mallory, and Sangam.

SECTION 7.4—BIOLOGICAL ENERGY SYSTEMS

Highlights

- Results in biotechnology research indicate that low-power, energy-generating elements will be produced commercially.
- Proton pumps and electron transfer systems have been created from lipids that are capable of self-assembly (and thereby forming membranes) and from proteins that perform pump functions.
- Proteins functioning as molecular motors have diameters of 20–50 Å.
- Energy is derived either from the oxidation of organic molecules to carbon dioxide and water through the process of metabolism or from the absorption of energy from light sources.

OVERVIEW

Electrical power systems are intrinsic elements of offensive and defensive operation in the modern military. Examples of these systems include communications, weapons detection, weapons guidance, and sensors. Associated with new technologies is the increasing burden borne by the infantry soldier; approximately 25–35 percent of the weight carried is related to power generation. Because of the high weight burden devoted to power supply, alternative power sources are in development. One source of energy may be based on biological system models or mimetics of biological power generators.

The new era of biotechnology has created opportunities for using biological systems or biomimetics as power-generating systems and as nanoscale motors. These electrical power systems are based on the ability of biological membranes to generate electro-osmotic gradients and proton pumps.

RATIONALE

During the past 2 decades, much has been learned about the mechanisms involved in the living systems' production of energy from nutrients and light. Living organisms generate electrical potentials, synthesize large organic molecules, and perform other tasks that require energy. Energy is derived either from the oxidation of organic molecules to carbon dioxide and water through the process of metabolism or from the absorption of energy from light sources.

The mechanisms involved in the oxidative phosphorylation metabolism of organic compounds and in the transduction of light energy to chemical energy require the generation of an electro-osmotic/electrochemical gradient across a membrane. The gradient is associated with transfer of electrons and/or protons, which results in the synthesis of high-energy compounds in the cell. The most ubiquitous of these high-energy compounds is adenosine triphosphate (ATP), which is recognized as a common currency of energy needs in a living cell.

In the metabolic process, the oxidation of the major nutrients results in the removal of electrons from the fat, carbohydrate, or amino acid substrate compounds and the stepwise transfer of the electrons in the mitochondrion to molecular oxygen, which then reacts with protons to form water. The removal of protons from the substrate and the creation of a proton pump across the cell membrane is an integral aspect of substrate oxidation. The production of ATP from adenosine diphosphate (ADP) by oxidative phosphorylation operates at an efficiency of approximately 40 percent and is, therefore, relatively efficient. The energy released by oxidation, not coupled to ATP production, is emitted as heat. Hibernating mammals use the oxidation of brown fat in a relatively uncoupled manner to generate heat needed to maintain body temperature.

In the photosynthetic process, larger organic compounds are generated from water and carbon dioxide using the energy of light. In this process, light interacts with a porphyrin-like tetrapyrrole component of chlorophyll in the thylakoid membrane of plant chloroplasts to cause the generation of molecular oxygen from water. The chlorophyll obtains an electron from the water as the molecular oxygen is generated. In this process, the electrons are passed from an antennae-like system of clustered chlorophyll molecules to a photochemical reaction center (PCRC). The PCRC has a particular arrangement of chlorophyll molecules that permit transfer of excited electrons from the antennae to electron receptor molecules. A proton pump, which generates ATP in a manner similar to that seen in the mitochondria during oxidative phosphorylation, is generated as part of the process. The time required for the processes is approximately 100 µs. In a related system, halophilic bacteria-like organisms, called halobacterium halobium, use a tetrapyrrole bacterial rhodopsin to generate a proton pump. For these systems to operate, an intact membrane is required, and the proteins acting as electron transfer agents are required to be organized in two dimensional (2-D) space. The proton pump is generated across the membrane, and the electron transfer process is generated in the plane of the membrane.

Because lipids are capable of self-assembling and thereby forming membranes, constructing proton pump and electron transfer systems is technically feasible. Such systems have been constructed. The generation of one molecule of molecular oxygen requires the transfer of four electrons. The production of 6 molecules of oxygen therefore requires 48 photons. Approximately 10,000 kJ are required to make 1 mole (mol) of glucose possessing 2,840 kJ.

From these considerations low power, energy generating elements will probably be produced commercially. These components can be used for generation of power for changing opaqueness of a visor, for driving sensors, or for read-write information storage components. In the Biological Technology section of Part III of the MCTL, the utility of bacterial rhodopsin as an information storage material is described.

Insertion of bioreceptor-ion channel molecules into lipid bilayers permits production of electrical switches at the nanometer scale. The lipid bilayer of electrically excitable tissues, such as muscle and nerve cells, contain molecular pumps that generate an ion gradient (hence a voltage drop of 70 mV) across the membrane. Sodium and potassium are the ions involved. Nerves and muscles also contain protein molecules that serve both as receptors and ion channels. The acetylcholine receptor (AChR) is an example of such a protein. When incorporated into a lipid bilayer 70-Å thick, these AChR molecules will bind to acetyl choline on one side of the membrane and cause an opening of the relevant ion channel. The ions will transiently cross the membrane resulting in a reduced gradient and lowering of the electrical potential.

LIST OF TECHNOLOGY DATA SHEETS
III-7.4. BIOLOGICAL ENERGY SYSTEMS

DATA SHEET III-7.4. PHOTOCHEMICAL REACTION CENTER SYNTHESIS/STRUCTURE (PRCS)

Developing Critical Technology Parameter	This is a two-photon capture system. The primary critical parameter is a miniaturized power source.

Parameter	1999	Projected by 2010	Nature's Limit
Highly conjugated porphyrin-like center with extended conjugated carbon chain. Compound 50-Å dimensions.	Isolated PCRC fragments of membranes with densely packed PCRC.	Densely packed arrays of PCRC aligned on surface.	Biomimetics can maximize PCRC packing density (nearest neighbor packing of PCRC is ultimate limit).

Critical Materials	Requires a light source (e.g., sunlight).
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	None identified.
Major Commercial Applications	Sensors (also military), charged-coupled devices (CCDs), data storage (read/write), camouflage, LEDs.
Affordability	None identified.

RATIONALE

The PCRC is used by chlorophyll in plants to capture photon transmission and transduce to chemical/electrical energy.

WORLDWIDE TECHNOLOGY ASSESSMENT

Brazil	●●	Canada	●●●	China	●●	Finland	●●
France	●●●	Germany	●●●●	India	●●	Italy	●●●
Japan	●●●	Netherlands	●●●●	Norway	●●	Pakistan	●●
Russia	●●●	Spain	●●	Sweden	●●●	UK	●●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Germany is the world leader in this technology, with competition from the United Kingdom and the United States. The 3-D structure of the PCRC was determined in Germany by Deisenhofer, Huber, and Michel. The leaders in this technology are the United States, Germany, Japan (Osaka University), and the United Kingdom, with strong efforts in Russia and the Netherlands.

DATA SHEET III-7.4. CHEMICALLY MODULATED ION CHANNEL

Developing Critical Technology Parameter

Parameter	1999	Projected by 2010	Nature's Limit
Voltage flux (mV)	a few mV to +20	–150 to +20	~ 150 (lipid membranes)
Process time (ms)	< 10		

Critical Materials	Proteins that form channels and where channels open/close in response to chemical or voltage gradients.
Unique Test, Production, Inspection Equipment	Production of lipid bilayer with ion channel proteins oriented appropriately.
Unique Software	None identified.
Technical Issues	None identified.
Major Commercial Applications	Sensors.
Affordability	None identified.

RATIONALE

Chemically modulated ion channels permit voltage flux to go from –70 mV to +20 mV in millisecond times by ion passage across gradient. The enabling phenomenon is the transduction of a chemical event to an electrical signal.

WORLDWIDE TECHNOLOGY ASSESSMENT

Brazil	●●	Canada	●●	China	●
France	●●●	Germany	●●●●	India	●●
Italy	●●	Japan	●●●●	Norway	●●
Pakistan	●	Russia	●●	Spain	●
UK	●●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The leading nations in this technology include the United States, Germany, Japan, and the United Kingdom. The 3-D structures of ion channels have been characterized in the United States and Japan.

DATA SHEET III-7.4. MOLECULAR MOTORS

Developing Critical Technology Parameter	The nanoscale molecular motors are protein molecules that exhibit vectorial movement along a surface. These proteins have diameters with dimensions of 20–50 Å. Dynein and kinesin are driven by the hydrolysis of ATP (~ 5–6 kcal/mol).
Critical Materials	Dynein moves in one direction while kinesin moves in the opposite direction. This behavior is analogous to the inverse flow of electrons and holes across a diode junction.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	None identified.
Major Commercial Applications	Switches (molecular).
Affordability	None identified.

RATIONALE

In recent years, proteins that function as molecular motors have been isolated from neural tissue. They propel themselves along a surface in a linear manner and are powered by the hydrolysis of a biomolecule and ATP. The attachment of several such motors to a particle will result in the propulsion of the particle in a fixed direction. Emerging biological energy system technologies are enabling for nanoscale motors.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●	China	●●	France	●●●●
Germany	●●●●	Japan	●●●●	Russia	●
UK	●●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The application of molecular motors into functional non-biological systems is a long-term (> 15 years) effort. Applications are in the early phase of development